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AN INTRODUCTION TO GEOLOGY

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BY

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PREFACE

THIS outline of Geology has been prepared primarily for use in schools. The place of geology in the educational system has recently been under discussion, and a committee of the British Association has prepared two reports in which the claims of the subject are set forth (*Ann. Rept.* for 1935, 1937; also *Nature,* 136, p. 708; 139, p. 251; 140, p. 595). It is hoped that this book will be useful to those who seek to introduce some geology into school courses, whether as an independent subject, as part of a scheme of "general science," or in connection with courses in geography. It may also be suitable for the general reader who desires a short formal introduction to the subject. While the relations of Geology with other subjects are suggested at various places in the text, little previous knowledge of any science is assumed.

It appears to me that the aim of such a course should be to awaken an interest in simple geological phenomena, to show something of the history of the changes affecting scenery and landforms, and particularly to build up a time-scale so that the relations of different events can be followed.

The general scope of the book is designed to cover the syllabuses embodied in the second report of the British Association committee. The treatment should be ample for a First School Certificate course or for the Subsidiary stage of a Higher course; pupils proceeding to the Higher Certificate with geology as a main subject would need to augment their reading, chiefly as regards mineralogy and the scenic aspects of British geology. While I have covered the topics mentioned in the syllabuses referred to, it must be realised that the interpretation of those syllabuses is my own, and doubtless some geologists would wish to have a

fuller treatment of some aspects of the subject, with a corresponding reduction of other sections. It has seemed to be desirable to give a fairly full account of the work of geological agents and of the chief rock types, but I have introduced as few names as possible in my introductions to mineralogy and palæontology. At most points I have refrained from including tables or summaries which might be learned by heart, believing that their preparation is better done by the reader; I have failed in my purpose if this book can be used as a cram book.

I have emphasised those sections of the subject in which students can make their own observations, believing that much of the teaching in geology should be closely concerned with familiar matters: this is stressed by dealing with outdoor observations in both the first and the last chapters.

The only section where a large body of the material must lie outside the experience of the pupils is in Chapter XIV, where a very general treatment of the more theoretical aspects (and of some rather speculative hypotheses) of earth structure is attempted; these have been included since it is realised that many readers will not have any further training in geology, and since it is desirable that they should know something of the meaning of isostasy and continental drift. I hope, however, that I have not given a one-sided or dogmatic treatment likely to mislead pupils who go on to further work.

The chapters are arranged in a convenient order for study, but many teachers may prefer to take the minerals or the sedimentary rocks immediately after Chapter I; in any event, Chapter VIII may very suitably be taken at an early stage, well in advance of Chapter IX, in order that a sufficient amount of practical work can be done on simple maps before folds and faults are dealt with. The order of treatment should depend on the location of the school, and the topics most easily illustrated in the neighbourhood should be dealt with first. Chapters XIII to XVI introduce more difficult matters and must come late in any treatment.

The illustrations are mostly diagrammatic, and it is desirable for the teacher to assemble a collection of pictures

from magazines and other sources to illustrate geological features. A much larger series of pictures than can be included in a small book can very soon be gathered; the geological photographs obtainable from the British Association and from the Geological Survey are of particular value. Few examples are quoted in the text of such common features as, for instance, stacks, perched blocks and river terraces, and their frequent occurrence should be emphasised by opportunity to examine varied illustrations rather than by memorising single instances of each.

In many areas the local museums will afford great assistance to the teacher of geology. Pupils of London schools, who may be able to do less actual field work (except on school journeys and on holidays) have the advantage of wonderful displays in the Geological Survey Museum and in the British Museum (Natural History).

At the end of each chapter some suggestions for practical work are given; it has been thought by some teachers that geology is a difficult subject for school courses because it does not afford suitable practical work. While it is true that pupils should spend some time examining and drawing specimens, however, there seems to be no reason why many other kinds of practical or even experimental work should not also be introduced. Some suggestions for work of this kind are given at the end of each chapter, but an experienced teacher will readily work out a much fuller scheme to suit his particular classes; if the work is done in the early stages of a school course the experiments may well serve as an introduction to scientific work, but if it is taken after the School Certificate stage much more detailed studies can be introduced.

In the report of the British Association committee the use of a microscope in school work was not suggested, but where microscopes are already available in connection with the teaching of biology it is desirable to allow pupils to see thin slides of such rocks as sandstone, limestone, basalt and granite under the microscope. The use of polarised light is not essential, but an ordinary microscope can now be adapted for polarised light at comparatively little expense.

In the section dealing with geological maps it has been decided to omit any references to graphical methods based on the use of strike lines. For the present purpose it appears more suitable to give a training in the general significance of structures and of their appearance on maps rather than to aim at the solution of geometrical problems; some teachers may prefer to use these methods, however, as a means to this end.

In writing this book I have received much help from a great number of friends, many of them former students, who are more closely concerned with school work than I am. I would particularly thank Miss N. M. Smith, Mr. James Davies (Caerphilly), and Dr. L. R. Moore. Most of my manuscript has been read critically by Miss Gaynor Evans and Mr. R. O. Jones, to whom I am very grateful for numerous suggestions. Prof. H. H. Swinnerton has discussed with me the proposals for experimental work, my colleagues, Dr. W. J. McCallien and Dr. J. Weir, have aided with several chapters, and Prof. S. H. Reynolds has kindly allowed me to make drawings from his photographs for *Figs*. 6, 7 and 14. To the officials of the Central Welsh Board, for permission to quote from recent examination papers, I would also express my thanks.

A. E. TRUEMAN.

13*th February*, 1938.

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CHAPTER I

THE STUDY OF ONE'S SURROUNDINGS

An Out-of-Door Study. The study of Geology is properly begun out-of-doors and there is no part of Britain where it is impossible to make a beginning. If the student lives in an area where the open country is easily reached he is perhaps more fortunately placed than one who lives in a large city, but both alike can find material on which to make a start; if he lives by the seaside, he will find lots of things which can be observed whether the coast is rocky or sandy.

The study of Geology may fitly be begun by the observation of such common features in one's surroundings as rocky crags or quarries or pits, the pebbles found in stream beds or the stones used in buildings. Some parts of Britain are ideal for the study of certain phenomena, but no part is lacking in interest, and for variety of geological feature there are few countries of the size of Britain which have so much to offer. Thus it was no accident that much of the pioneer work in the science of Geology was carried out by British geologists.

Laboratory Work. Not all the practical work of a geologist is done out-of-doors. There he must make many of his observations, but much material must be taken to the laboratory for more careful examination by tests in which the resources of other sciences must be drawn upon.

To begin with, it is useful to collect samples of as many different rocks as can be found, to note the ways in which they break, to find how easily they can be crushed or ground up, to examine with a lens the powder so formed: in these ways much may be learned of their properties.

Soil and Rock. If you begin to dig in any garden or

field, a few feet, or perhaps only a few inches, will take you beneath the soil, often to a stony mixture which is called the sub-soil. In almost any locality a hole dug in the ground (such as a road-cutting, a trench for the laying of pipes or for the foundation of a house) will show the relations of the soil to the sub-soil and of the sub-soil to whatever lies beneath. In many places the section will be something like that shown in *Fig.* 1, the solid rocks showing signs of being broken up as they are traced towards the surface, the broken fragments being smaller and more

FIG. 1. Rock, sub-soil and soil. A sandstone quarry at Temple Cloud, Somerset.

detached in the higher parts of the sub-soil, and the subsoil passing gradually up into soil.

This close relation between the solid rock and the overlying soil is frequently to be observed, and it is apparent that in many places the soil has been formed, to a large extent at least, by the breaking up of the rocks. There is thus a close connexion between the nature of the rock and the character of the soil; a sandstone is overlain by a light sandy soil, a clay by a heavy clayey soil.

Sometimes the relation between soil and the rock beneath it is not so close. This is the case, for instance, where there are steeply sloping hillsides; here the soil tends to slip or creep slowly down the hill. The hillside may have little soil, while a much thicker soil, possibly derived from a variety of rocks (if they are present on the hill above) may be found on the lower ground in the bottom of the valleys.

Rocks. Beneath the soil and sub-soil, often at a depth of only a few feet below the surface of the ground, solid rocks are usually met with. They can be seen in cliffs, in cuttings and in quarries, and it is useful to visit such places

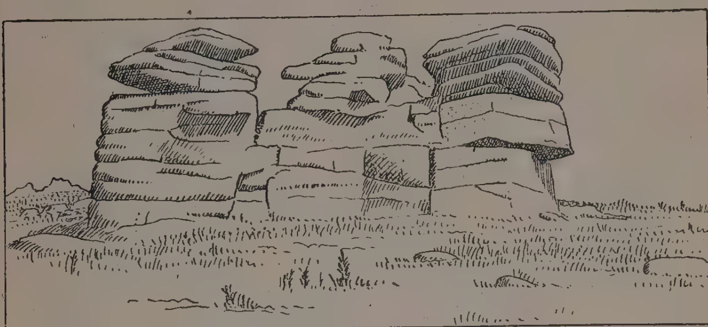


FIG. 2. Weathering of granite. Little Mistor, Dartmoor.

where the rocks are exposed in order to get some idea of their nature and occurrence. They differ greatly in different parts of Britain, but in many parts of England and Wales and of the south of Scotland, the rocks appear to be made up of a succession of beds or layers, one placed above another in a regular succession. Whether they are sandstones or clays or limestones, exposed rocks will almost always show something of such a bedded structure. Each bed is sometimes called a *stratum* (plural, *strata*) and these rocks may be known as *stratified* rocks. The beds represent the original layers in which the rocks were formed.

The beds may be horizontal, or they may be tilted at an angle to the horizontal. If they are so tilted, they are said

to *dip*. Even at this early stage of our examination of such a section it is useful to form some idea of the amount of the dip of the rocks before us, and to note whether the beds are dipping gently (*Fig*. 78a) or steeply (*Fig*. 78b) or are quite vertical (*Fig*. 77).

Generally the beds were first formed as almost horizontal layers, and the dip which they show thus represents the amount to which they have been tilted from their original position.

Besides having this bedded structure, many strata are cut more or less distinctly into blocks by regular sets of joint-planes. Frequently these *joints* are arranged at right

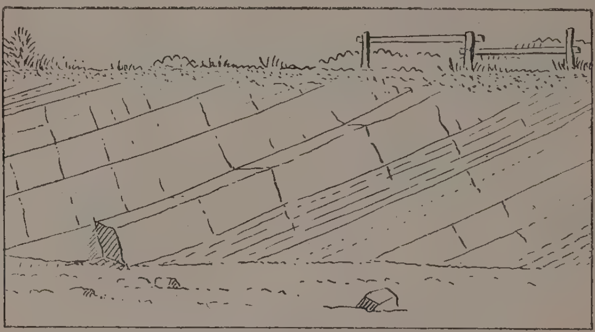


FIG. 3. Quarry showing dipping beds.

angles to the bedding-planes, and often there are two sets of joint-planes in a given stratum, approximately at right angles to one another. In such a case the stratum is divided up into more or less rectangular blocks, the shape and size of any block which can be quarried thus depending on the thickness of the bed and the distances between the joints. Usually the bedding planes are prominent and the joint-planes are much weaker, but in some cases, especially where the beds are thick and some of the joints are close together, it is not so easy to determine which is bedding and which is jointing: a layer of pebbles or of fossils or a band of different colour will usually indicate the direction of the stratification.

Origin of Stratified Rocks. It will be useful to look more closely at some of these stratified rocks, for they often yield evidence of the ways in which they have been formed. For instance, on the face of many beds of sandstone distinct traces of ripple marks are found identical with those seen on a sandy beach. Now we know that such ripples are only formed on the bottom of shallow waters, and this throws some light on the origin of the sandstone. In other sandstones or clays, are cracks like those formed on mud banks which are left dry and exposed to the sun's heat; such sun-cracks among stratified rocks indicate that they were formed in water which at times dried up or disappeared, leaving them bare to be baked by the sun, before they were submerged again and buried under other deposits.

In many rocks, too, fossil shells or other organisms give evidence of the conditions under which they were formed. The presence of fossil corals generally implies clear sea water; many types of shell are proof of formation in the sea, while the occurrence of numbers of fossil leaves indicates that the rocks were formed in an area not far away from land.

By such simple means it is possible to get some idea of the conditions under which most stratified rocks were made. It is found that most of them were formed under water, whether the sea or lakes, though a much smaller proportion represent accumulations of material laid down on the land.

In whatever place they were deposited the greater part of the stratified rocks have been formed from *sediments* of one kind or another, mud or sand or the hard parts of shell fish or a variety of other materials; such rocks, consisting of sediments whether laid down under water or on the land, are known as *sedimentary rocks*.

Many such sediments must have accumulated very slowly, in some cases possibly only a fraction of an inch having been laid down every year, and although other deposits may have been deposited more rapidly, it is obvious that a pile of material hundreds of feet thick, such as can be seen in many quarries, must have taken a great time in its formation.

Hardening of Rocks. When the sediments were first laid down they must in most cases have been soft and unconsolidated; clay rocks were once oozy muds, sandstones were once loose sands. If a sample of clay is collected and placed in water it may break up into a soft mud, while many sandstones can easily be crushed up again into their constituent sand grains. It is clear that these sedimentary rocks have been hardened or consolidated in some way since the original sediments were laid down. In some cases this has resulted from the pressure due to the piling above them of hundreds or thousands of feet of other strata, the weight of this mass of material so compressing the grains together that they form a more or less solid mass. If the volume of wet mud yielded by the breaking up in water of a piece of hard clay be compared with the original volume of the sample taken, a large increase will usually be noticed; it is apparent that the clay rock had undergone considerable compression. In the case of some clay rocks the bulk of unconsolidated mud from which they have been derived was probably six or seven times that of the rock at present.

On the other hand, sandstones have not suffered much reduction in bulk since the time when they were laid down as sands, and the hardening of such rocks has usually been brought about by the introduction of some further material which has acted as a kind of cement between the grains. Calcium carbonate is the commonest material which acts in this way.

It may be useful to note here that to the geologist all sediments, whether consolidated or loose, are known as rocks. Sand and the sandstones which may be formed from it, mud and the clays, shales and slates to which it gives rise, soft peat or hard coal, all are rocks in the sense in which we shall use that term. But there are other varieties of rock, and the definition of that term may thus be postponed for a little.

The Extent of Strata. When sedimentary rocks are seen at the surface it is generally only a portion of a bed or stratum which is visible. For instance, in the section shown in *Fig.* 4 the dipping bed of limestone (L) extends

from top to bottom across the quarry, but it is extremely unlikely that it ends where it meets the floor of the quarry. It has been shown in countless instances that beds which are seen dipping down in such a way continue for some distance, deeper and deeper into the earth's crust. Thus a well dug some hundreds of yards to the left of the place shown in the diagram would in all probability reach the limestone, though at a depth of several hundred feet. It is on the basis of the probability of the extension underground of beds which are visible for a limited distance that pits are dug to great depths, and many of the operations of mining

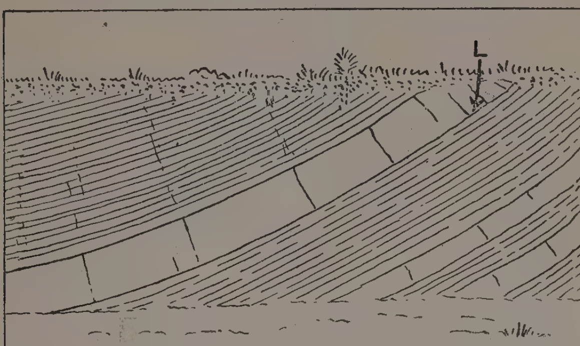


FIG. 4. Section showing a dipping limestone (L).

are undertaken. As we shall see, such an underground extension may be cut short in various ways, but for the present the fact that exposed portions of strata are but a small fraction of their concealed extent is extremely important.

It may be interesting at this point to notice another aspect of this same question. The bed in *Fig.* 4 of course ends abruptly where it meets the surface of the ground, or where it passes into the sub-soil. It is not perhaps so easy to realise that where the bed ends at present has no relation to its former extent, and that it used to stretch upwards above the present surface, perhaps for hundreds or thousands of feet. This portion of the bed has been worn away,

by the work of the weather or other agencies, as we shall see later. The surface of the ground merely represents, in most cases, the level to which the wearing down of the rocks has advanced, and though the wearing takes place slowly the position of the surface, strictly speaking, is only temporary: many years ago it was higher than at present and there was more of the particular stratum existing than there is now, while after a long period still more of the bed will have been worn away.

We may thus find it useful to recognise that any inclined bed which we are able to observe passes down into the earth for some distance and formerly extended upwards into the air.

Fossils. At one time the term fossil was applied to any object, peculiarly shaped or marked, which was dug up from the ground. We now limit the word *fossil* to an object which is of organic origin; that is, to something which either formed part of a living organism, plant or animal, or bears some indication of such an organism. The teeth or bones of a fish, the skeleton of a coral, an impression of a leaf, the footprint of a reptile, are all fossils.

Such objects may commonly be found in nearly all sedimentary rocks. The fossil leaves and stems which may be found on the rubbish heap of a colliery, the shells which may be found in many clay pits and limestone quarries, are typical of what may be seen in many areas of Britain. There is scarcely any part of southern or eastern England where abundant fossils of one kind or another may not be found.

Fossils of marine animals are extremely common in many places, not only by the sea shore, but inland, as in the limestones which form the mountains of Derbyshire and West Yorkshire. Since many of these shells or corals must represent creatures which formerly lived in a sea, we are almost bound to conclude that the sea used to cover many parts of England which are now far from the coast, and some of which are very high above sea level.

Any consideration of the occurrence and distribution of fossils leads us to the view that in the geological history

of Britain there have been great changes in the distribution of land and water. Evidence for such changes is also seen in most other parts of the world. The mountains, whose stability seemed to be beyond question, are recognised to include upraised portions of old sea floors, bearing the remains of animals; sea shells may be found in the rocks on the summit of Snowdon. The earth is full of signs of this instability, and of these vast changes which have affected the continents.

In the study of geology we are able to trace these changes, to arrange them in a chronological sequence, and to see some of the causes which have brought them about. The early pioneers of geological study, less than two centuries ago, were collecting information and making deductions precisely as you are doing now; sometimes their conclusions were erroneous, and fresh facts necessitated new hypotheses. The science of geology, as we know it now, has taken shape within little more than a hundred years. Even now there is still much to be learned and many new kinds of fossils still await discovery.

Types of Rock. So far we have only concerned ourselves with the general observation of sedimentary rocks and their structure. There are two other broad classes of rocks, *viz.*, the igneous rocks and the metamorphic rocks.

Igneous rocks are those which have been formed by the solidification of hot molten material; they used to be thought of as "fire-formed" rocks, while sedimentary rocks were regarded as "water-formed." The most obvious example of an igneous rock which will occur to you is lava, poured out in a molten stream from a volcano and solidified to form a rock either on the land or in the sea. There are great areas of volcanic lavas, the products of volcanoes long extinct, in different parts of the British Isles, notably in Antrim, in the Inner Hebrides, in North Wales and in the Lake District. But there are other important igneous rocks which are not of volcanic origin, though formed from material similar to that which was poured out on the surface as lava; these other igneous rocks represent material which was forced up into the crust but did not

reach the surface, and cooled and solidified while underground. Among such igneous rocks granite is the best known example. Like most igneous rocks it is clearly of crystalline character; in granite the crystals are distinctly recognisable although in some igneous rocks they are too fine to distinguish by the naked eye.

Such masses of granite are seen in Dartmoor and Land's End, and elsewhere in England and Wales, and in various parts of the Scottish Highlands. Granite is not a stratified rock, though it has distinct joints and in some cases it has a nearly horizontal set of joints which at first sight resembles bedding (*Fig.* 2).

Metamorphic rocks are most characteristically seen in the Highlands of Scotland, where they occupy great areas. They include rocks which were both of sedimentary and igneous origin, but which have suffered such complete alteration owing to heat or pressure that many of their original characters have been destroyed; in some cases it is almost impossible to tell what was the exact nature of the original rocks. The features of metamorphic rocks are thus often difficult to understand, and while the student who lives in the Highlands must begin to make observations on them, most students will find it convenient to defer their study until later.

Minerals and Rocks. It was formerly common to divide the objects met with on the earth into those belonging to the animal, the vegetable and the mineral kingdoms: we still speak of railway trains conveying coal or stone as mineral trains. But in our science we use the term *mineral* in a more restricted sense.

In many areas it will be possible for the pupil to obtain a piece of granite from material used either in roads or buildings. If such a piece is examined carefully three chief constituents will be noticed: a glass-like mineral often with curved faces on a broken piece of rock, a whitish or pink mineral with rather smooth or fairly flat faces where it is broken, and a very lustrous constituent in thin flexible layers. The first constituent is called quartz, the second is felspar, and the third is mica, and we shall examine them

in greater detail later. If you take a piece of granite and break it up into pieces an eighth of an inch or less in diameter you will find that you can separate these into three unequal heaps, each of fairly uniform character.

These three constituents (quartz, felspar and mica) are different minerals, each has a definite chemical composition, different from that of the others; each has its physical properties, such as a distinctive hardness. In certain granites there are felspar crystals several inches across; in some places even larger crystals of felspar or mica occur, but they very rarely exceed a foot or so in length.

FIG. 5. Granite, Cornwall. Natural size. Felspar, white; quartz, dotted; mica, black.

These considerations help to make clear the differences between minerals and rocks. A *mineral* is of definite chemical composition (though in some cases this varies within narrow limits), while a *rock* is an aggregate of particles possibly of several minerals, each of entirely different composition. Each individual mineral grain or mass is of limited size, but rock masses are always more extensive, often stretching for miles: even a bed of rock only a fraction of an inch thick may be traced for a long distance. Granite is made up of three different minerals; sandstone on

the other hand is a rock consisting mainly (or even entirely) of grains of one mineral, quartz.

The mineral grains found in many rocks are too small for individual study without a microscope, and a student of minerals seeks for places where large specimens can be found; very often these occur in veins, which sometimes run between the beds of rock and sometimes cut across the beds (*Fig.* 13). Where veins containing ores of iron or other materials of economic value are being, or have been mined, excellent examples of many minerals may be collected on the rubbish heaps near the mines. Minerals may be obtained in this way in various parts of Britain. There are, however, many veins containing minerals of no particular value. In numerous localities they can be seen in cliffs or quarries; for example, in limestone quarries veins of calcite may frequently be seen. There are few places where some mineral specimens cannot be found.

Observation of Rivers and Sea Coasts. But there are many ways in which a student may begin the study of geology even if no rocks or minerals are easily examined in his district. The observation of a river, a torrent or a brook will afford a useful basis for the appreciation of some of the agents of change which have led to the modification of the landscape. The torrent sweeping along boulders and pebbles during its time of flood shows how material is being carried from higher ground to lower. That a quiet river lower down the valley is continuing the process may not at first be obvious, but if we take home a quantity of river water and filter it we shall find that it contains quite an appreciable amount of fine mud which the river is bearing seawards, while if we evaporate some of the water to dryness the presence of dissolved solids will also be apparent. In short, all running water is helping to carry rock fragments (of various sizes) on their downward path. The amount being carried may appear small, and so perhaps it is at any moment, but if a similar quantity is taken continually throughout the day, and for every day of the year, and this has been happening for thousands of years, it will be seen that it is an extremely important factor. In this

way the land is being slowly worn down, valleys are being excavated and the debris is being taken into the sea.

If we pay more attention to the streams or rivers of our own area we can learn more of these processes, as will appear later. We see the torrent cutting deep gashes into its bed, or the quiet river undercutting its banks and causing the edge of the meadow to slip into the water.

Similarly the student living near the sea is able to watch the work of the waves, pounding at the cliffs or breaking up and rounding loose stones. He may see the collapse of buildings as the waves break down cliffs or sea walls, or the piling up of banks of boulders or shingle, and so may gain some knowledge of the way in which the coast line changes and of the importance of the sea as an agent of geological change.

External and Internal Forces. In these ways we may recognise the existence of various agents which are continually at work modifying the form of the earth's crust. Working very slowly, the rivers and streams, the sea, rain, ice and frost, all tend to alter the shape of the land. Besides these changes, all due to forces external to the earth, there are others, due to forces originating in the interior, whose existence may be glanced at here. There are, for example, volcanoes, from which hot material is forced out from beneath the earth's crust, and there are earthquakes due to movements occurring at some depth. But these are only the more familiar manifestations of some of the forces which have raised and lowered continents and have built mountain chains.

The Present as the key of the Past. By the action of the various agents referred to above great changes have been produced in the earth's surface. Some of these agents, as we have noticed, act exceedingly slowly, and any considerable effect can only have been achieved after the lapse of a great period of time. Yet if a river gradually carries material towards the sea it will lead in time to the production of a great valley; there are many reasons for believing that most valleys have been formed this way.

Formerly it was supposed that many valleys, especially deep chasms and gorges, had resulted from great convulsions of the earth's surface, from enormous earthquakes (" volcanic " action was often thought to have influenced such areas). Indeed, by many of the early geologists it was thought that the earth's history had been marked by a series of great catastrophes, of which the Flood was the last, while between these times of great unrest there had been periods of quiet and stability like the one in which we are living.

This catastrophic theory of the earth's history was challenged by several geologists, but its final overthrow was chiefly due to Charles Lyell, who has aptly been called the " father of modern geology." Lyell studied the natural processes which are at present altering the face of the earth, and he showed how these agencies are adequate, given sufficient time, to have produced the features in the landscape which are familiar to us. So there grew up the " Uniformitarian " view, in which it was suggested that the earth's history had not been marked by tremendous catastrophes, but had been relatively uniform. Thus, although there may have been earthquakes and volcanoes greater than those of which we have historic records, it is believed that they were not incomparably greater; although large parts of continents have been submerged beneath the sea, this has not resulted from the sudden sinkings of the land, but long-continued changes in the level of the land and sea (such as we know to be taking place almost imperceptibly in parts of Europe) have ultimately produced widespread changes.

Extensive observations of phenomena in all parts of the world have tended in general to confirm this view of earth history; conditions have perhaps been less uniform than some early advocates of uniformitarianism believed, but it has become increasingly evident that the origin of mountains and valleys and coasts and of many rocks can only be understood after a study of the changes taking place at the present time. The study of the present is the real key to an understanding of the past.

What is Geology? We are now in a position to appreciate the extent and nature of the science of Geology. At its widest, Geology is the science of the earth. It includes the study of the form of the earth, of its origin and of its relations to the heavenly bodies; in this direction geology thus reaches out to astronomy. It includes the study of the interior of the earth, and of its nature and structure; this study is based mainly on physical observations of various kinds. But geologists are chiefly concerned with the more accessible parts of the earth's crust, including those parts, down to a depth of a mile or more, which can be reached in mines or by drilling deep holes (such as those made in the search for oil or water). The geologist is thus concerned very closely with the study of the materials of this part of the earth's crust, and so the study of rocks and minerals must form an important part of his work: he needs to know not only their chemical composition but their structure and their arrangement in the crust, he needs to determine their history, and so to build up an historical account of the changes which have occurred on the earth's surface. In this latter task the fossils are of first importance, and as these reveal something of the history of life, geology is linked with another science, biology. Still further, the geologist studies the present landscape, the shapes of the surface features and the agents leading to their modifications.

Geology thus covers the investigation of a wide range of phenomena, most of them familiar and many of them intimately related to the daily life of mankind; the geologist is concerned with the location of minerals and oil, the stability of foundations, the search for supplies of fresh water, the protection of coasts from destruction by the waves and a host of other problems.

SUGGESTIONS FOR PRACTICAL WORK

A most useful beginning may be made by collecting specimens of all kinds of rocks, minerals and fossils, both from around the school area and from friends who have travelled. Systematic collecting should be encouraged; students should learn to make tidy "hand-specimens" of rocks, and to use a geological hammer (with one end

square and one chisel-shaped). All samples should be wrapped in newspaper immediately for carrying home, unless very fragile, when other packing is needed.

Other field studies may be made according to the suggestions given in the text; field sketching should be practised.

The material collected should be examined and roughly classified in school; samples of rocks and minerals should be broken and powdered in order to get familiar with their hardness, lamination, grain size, etc. Small hammers and steel blocks will be useful for this purpose here and at later stages.

QUESTIONS.

1. Give an account of the quarries and mines situated in the area with which you are familiar. Name the various products.
2. What is the difference between a mineral and a rock in the sense in which the terms are used by geologists? Name three minerals and as many rocks as you can.
3. What evidence is there that the area where you live has undergone great changes in the past?
4. The earth is said to be many millions of years old. Discuss some of the evidence on which this view is based. (C.W.B.Hr., 1928.)

CHAPTER II

WEATHERING: GROUND WATER

As we have already learned, the rocks preserve a record of some of the happenings of the past, often of the very distant past. If we are to be able to read these records it is essential that we should know something of the nature of the changes which are taking place at the present time, for the study of the processes in operation at the present gives us a key to the understanding of the past.

Weathering. We can get some idea of the way in which rocks decay by examining old buildings, by comparing the masonry in the exposed and the sheltered sides. It is familiar to all of us that old carving or the lettering of tombstones may become almost completely obliterated in the course of years. Some rocks, of course, withstand the effects of the weather better than others, and it will be noticed that the inscriptions on certain types of tombstone are illegible after fifty years or so, while others preserve much detail after several centuries. Slowly, however, all rocks suffer to some extent in our climate.

It needs no imagination to understand that the changes which are to be detected in the stones of old buildings are closely comparable with those which occur in the exposed rocks in cliffs and crags. The decay of stone is one of the factors responsible for the modification of the land surface.

Some of the causes of this decay are not difficult to understand; the greater rate of disintegration in the more exposed parts of buildings shows the influence of the weather in bringing about this change, and the whole of the natural processes involved may usefully be included in the term "*weathering*." Many different processes contribute towards the weathering of the rocks: the most im-

portant are the changes in temperature and the action of frost and rain. It will be useful to consider briefly how each of these acts.

Changes of Temperature. In the hot sun of a summer day, the outer part of the exposed stone is heated up considerably, to cool again in the night; the rising and falling of the temperature is accompanied by a corresponding expansion and contraction of the material. But the deeper parts of the stone do not change their temperature so much or so regularly, and thus the outer layers are in an almost continual state of strain. The effect of pouring boiling

FIG. 6. Spheroidal weathering in dolerite, Millers Dale, Derbyshire.

water into a cold glass vessel (especially a tumbler with a thick base) illustrates something of this disruption which occurs. From time to time layers of stone split off or the outer surface gradually crumbles away. In some rocks the tendency of the material to peel away or shell off in rather concentric layers gives rise to what is sometimes known as spheroidal- or "onion-weathering" (*Fig.* 6), in others more or less flat films break away and leave regular surfaces.

Naturally these effects due to changes in temperature are greatest in those regions where the daily range of tem-

perature is great. In some hot deserts the rock faces are heated during the day but very rapidly cooled owing to the quick radiation into the clear air at night; the range of temperature has been estimated as 140° F. in some cases.

In certain rocks, temperature changes may lead to a strain in another way. If a rock consists of different minerals (as in the case of granite) the rates of expansion of the various minerals (or more precisely, their coefficients of expansion) will be different; thus each mineral will undergo a different degree of expansion or contraction during a given change of temperature, and internal stresses will be set up which will lead ultimately to the breaking apart of the grains.

Frost. The effects of frost action chiefly depend on the expansion which occurs when a given volume of water is frozen into ice. The water occupying the pores in the outer layers of a rock expands when it freezes; if the pores are quite filled with water, the ice tends to push apart the mineral grains on either side. Probably the action is not quite so simple as this in all cases, but the effect of frost action is generally to shatter the surface rocks, yielding angular fragments. The effect is necessarily greatest in regions where most frost occurs, such as the mountain summits in Britain. Frost-shattered peaks generally have a very jagged and irregular pattern, with sharp and needle-like projections, such as are well seen on the higher parts of such Lake District mountains as Scawfell, and on Cader Idris in North Wales.

The effect of frost on soils may often be observed. The expansion of the ice increases the distance between the solid particles in the soil, so that when a thaw occurs the soil is often left in a loose and spongy state: as a result it is often swept away by rain water. In a similar way, though more gradually, frost may help in the disintegration of solid rocks.

Rain. As rain falls through the air it dissolves some gases, particularly carbon dioxide, a gas which forms only about 3 parts per 10,000 in the atmosphere. Water containing it has something of the effect of a weak acid on the

rocks on which it falls; by the help of the dissolved carbon dioxide it is able to attack chemically certain substances in the rocks, and some, especially the carbonates, are themselves dissolved. Where the rocks consist of grains held together by a cement of carbonate (a common condition, p. 6) the grains may be set free by the cement being dissolved, although the grains themselves may be unaffected; many of the grains of sandstones consist of the mineral quartz, which undergoes no chemical change in these conditions, and yet the sandstones are disintegrated. Dissolved oxygen also affects many minerals; much as iron becomes rusty in contact with damp air so certain iron-bearing minerals become red or yellow on combining with more oxygen in the air. The rusty colour of many weathered rocks is simply due to the oxidation of their iron compounds; many rocks with such a brownish crust are blue or green in their unweathered parts. For this reason it is always essential to make sure that a "fresh" piece of rock is being examined. There are many quarries which seem to be in rusty coloured rock until a fresh sample is seen with an unweathered face: many blue clays are brown in the weathered parts.

The effects of rain thus differ according to the nature of the rocks, but generally they tend, directly or indirectly, to the breaking up of the particles; loose particles are then readily washed away and a fresh surface exposed to weathering. Where rain falls on a slope made up of a mixture of pebbles and boulders with fine sand or clay, the softer material is soon carried away and the pebbles are left capping tall pillars. Minute pillars of this kind may be seen on many slopes after rain, but tall pillars are best known in parts of Scotland and the Tyrol (*Fig.* 7). Simply wetting many rocks will lead them to break up; many clay rocks will form a mud if they are once wet.

Products of Weathering. The various agents of weathering may be said to work in two ways, physically and chemically: in some cases they merely break up the rocks into fragments or grains without altering them chemically in any way, but in other cases there is a chemi-

cal alteration or decomposition, leading to a change in the nature of some of the original material.

The material worn from the rocks by these processes may remain for some time in close proximity to the solid rocks: it may lie as part of the soil immediately above the rocks from which it was derived (*Fig.* 1). There is a tendency, however, for it to slip downhill, and gravity exercises a great influence in the movement of all the products of weathering. In order to check such movement of the soil in hilly regions some form of terrace cultivation has frequently been adopted.

FIG. 7. Earth Pillars, near Botzen, Tyrol.

Along the base of many cliffs are great heaps of angular fragments which have fallen from the rocks above and which form a steep mass which slips and moves each time a new fragment falls on to it. Such *screes* or talus slopes are commonly seen under precipices; those of Wastdale in the Lake District are very famous (*Fig.* 8). The scree material represents a natural heap, piled up at the steepest angle at which the blocks will rest (*the angle of rest*), and so a climber stepping on such a slope will dis-

turb its equilibrium and may find the boulders slipping down with him.

The movement of the products of weathering is not always so simply an effect of gravity, for they may be transported by water or blown by the wind. The effect of the wind may be seen in the moving of dust during dry weather, from ploughed fields or other places where loose soil is exposed. Evan when grass covers the fields the soil is bared in places by rabbits and other animals, while earthworms, eating fine mould and passing it through their

FIG. 8. Screes, Wastwater, Lake District.

bodies, bring up an enormous quantity to the surface in their castings. The effects of these and other organisms on the soil and its distribution are often of great importance.

Soil. The soil may be regarded in part as a blanket of disintegrated rock fragments, either derived from the rocks beneath or transported from some higher situation: the soil, however, has some material of organic origin, derived mainly from the decay of plants. The plants themselves also help in the growth of soil by promoting rock

destruction; the penetration of roots into the joints and crevices of the rocks leads to their being broken up.

Geological Agents. The agents which have produced the effects described as the weathering of the rocks are known as *geological agents*. There are other geological agents, some of which accomplish other kinds of destructive work; certain agents do work of other types, some carrying away the material resulting from various kinds of destruction, others arranging the transported material to form new deposits in the sea or in valleys.

Geological agents which lead to the breaking up of the rocks and to the transporting away of the resulting debris are known as *agents of denudation*.

Besides those agents mentioned under weathering, denudation is also promoted by the wind, by running water and ice, and by the sea. In the following pages the work of these agents, both as regards denudation and deposition, is briefly examined. It may be emphasised that no attempt is made to give a very rigid classification of the work done by the various processes, but in the survey which follows some reference is made to the results of all the more important processes.

Work of the Atmosphere. The work of the atmosphere is strikingly seen in its power of transportation. The movement of sand grains along the sea shore (or over the land where dry sand is present) may be very impressive in a strong wind. When such transported material is piled up against a barrier it is possible to get some idea of the quantity of material which has been moved.

Some of the most important examples of material moved by the wind are to be seen in *sand dunes*. These are particularly characteristic of sandy shores which are exposed to winds blowing inland from the sea; as the wind crosses the stretch of sand left dry between tides it carries grains above high-water mark, and forms long mounds or ridges roughly parallel to the coast. Such dunes are in some cases two hundred feet or more in height; they are common on many parts of the coast. In many places the dunes have advanced for some way inland, often ruining good agricul-

tural land; there are large areas in Moray in the north of Scotland which were devastated in that way some three hundred years ago, while in South Wales the old villages of Margam and Nicholaston were buried under the advancing sand.

The movement of a sand dune may best be understood from a consideration of the section in *Fig.* 9. Sand grains are blown by the wind up the slope from A to B, when they may be regarded as falling down the steeper slope from B to C; here they form a slope determined largely by the angle of rest of the grains. If you have walked over the sand hills near the coast you will be familiar with the difficulty of climbing these steeper slopes, where the sand falls away with you at every step.

It should be noticed that the continuous transfer by the wind of particles from A to the slope B C will gradually

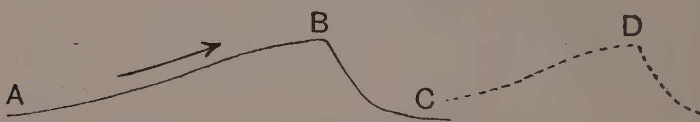


FIG. 9. Diagrams to illustrate the movement of sand dunes. Arrow showing direction of prevailing winds.

lead to the forward movement of the dune, ultimately to a position in which the crest is at D. It is in this way that dune movement occurs; it can be checked if a growth of some vegetation can be secured on the windward slope, for this prevents the free movement of the grains. Large dunes have thus been fixed and much valuable land saved from ruin by planting such sand-loving species as the marram grass (*Psamma arenaria*).

Extensive deposits of wind-blown material are of course found in many desert regions, as in the Sahara. In Europe and Central Asia there are also thick accumulations of fine loam or dust, known as *loess*. These accumulations are regarded as partly of æolian origin; in places they are more coherent than ordinary dune sands, and they have been excavated for cave dwellings in China.

Where the wind is carrying large quantities of sand grains it is enabled to do mechanical work on exposed rock surfaces against which the grains are hurled, much in the way in which a " sand blast " is used for producing frosted glass or for cleaning metal: the glass of windows in some exposed positions has become frosted by natural means, while rock faces in desert regions may be polished by this type of wind action. Since the wind near the ground carries more sand grains than at greater heights, the bases of projecting masses of rock tend to be cut away more quickly than the upper parts; the rocks are thus undermined and form curiously shaped pillars and tables, such as those found commonly on the Pennine moors north and west of Leeds, and elsewhere.

Surface Water and Ground Water. Of the rain (or dew, snow and other forms of precipitation) which falls on any area, a portion evaporates or is taken in by plants and is returned to the air, accomplishing no geological work; a portion runs off, as *surface water*, to join streams and rivers; a portion sinks into the ground, to become *ground water*. The ratios of surface water to ground water will vary in different circumstances. Where the rocks are very porous so much water may sink in that there are few surface streams, while if clays form most of the ground there are many streams and little water passing underground. Steep slopes also promote run-off rather than percolation.

In the remainder of this chapter the more important geological aspects of ground water are dealt with, while surface waters form the subject of the next chapter. Although this arrangement is convenient, it must be recognised that ground water, after passing for some way underground, may rise to the surface in springs and augment the surface waters.

Porosity and Permeability. It is apparent that the quantity of water passing underground is related closely to the porosity of the rocks. That there is great diversity in the porosity of different rocks may easily be shown by determining the weight of water absorbed by dried cubes of

sandstone, chalk and granite. Chalk and some sandstones will absorb water equal in amount to 40 per cent. or more of their own volume; granites will absorb less than 1 per cent. of their volume.

The passage of water into or through a mass of rock is not merely dependent on the proportions of the total pore space, however; the sizes and continuity of the pores have much greater effect. For instance, water will penetrate a heap of gravel (in which the "pores," or the spaces between the pebbles, are conspicuous) in a few seconds, while it takes water several hours to pass through a foot of chalk in which the total pore space may actually be greater in proportion but in which the pores are of microscopic dimensions. This may be shown very roughly by soaking a lump of chalk for some time in water coloured by some dye, and then cutting the chalk across, the uncoloured centre showing the slowness of penetration: chalk has porosity but is not so permeable as sandstone: clay is almost impermeable.

The movement of water underground is often affected by the joints in the rocks more than by the pores. In granite country, for example, most of the water finds its way along the joint planes.

The Water-Table. It will be useful to consider what happens to rainfall, newly fallen and just sinking into the ground, in an area made up of sandstones or other permeable rocks. The water will usually continue to pass down to greater depths until it reaches rocks in which all the pores are already full of water, and it will thus be added to this underground store. While the porous rocks continue down to a greater depth, the pores are water-filled. We may thus distinguish two broad regions underground in such an area, an upper region where the rocks are practically dry (except for water from recent rainfall which is on its way downwards) and a lower region where the rocks are completely full of water. The boundary between these two regions is called the *water-table;* it is a fairly definite surface, not always level, rising under the hills and dipping under the valleys, as shown in *Fig.* 10.

During times of heavy rainfall the level of the water-

tables rises, while during droughts it falls. Thus a well at W (*Fig.* 10) might easily be expected to run dry during a drought, for if the water-table fell a short way the well would be wholly within the dry rocks.

Where the water-table reaches up to the bottom of a valley a stream may be expected, but during a dry period the lowering of the water-table may temporarily leave the valley dry. Numerous temporary streams known as "bournes" in the Chalk country of England are due to such seasonal fluctuations in the levels of the water-table. Most of the valleys in the Chalk, as well as in other limestone and sandstone regions, are ordinarily dry. Many dry valleys, however, are typical river valleys which were formed when the water-tables were higher, and some of them hold streams after periods of excessive rainfall.

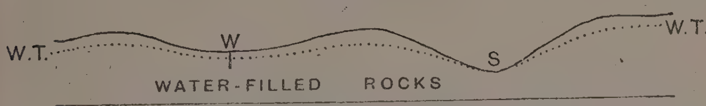


FIG. 10. Section to show form of water-table in thick porous rocks.

Springs. Ground water is chiefly found in permeable rocks, and where permeable and impermeable rocks are found in association the distribution and movement of the ground water are to a large extent influenced by the dip and arrangement of the beds. The examples illustrated in *Fig.* 11 will help to make clear the relations of these structures to the ground water. In *Fig.* 11a the sands capping a rounded hill are resting on impermeable clays; the ground water in the sands (resulting from rain which falls on the area they occupy on the hill-top) is held up by the clay. Naturally there is a tendency for the water to seep out at the edges, where there may be some distinct springs but where there will almost certainly be a belt of ground which is wet and sticky except in the driest weather.

If the junction between the sand and clay is dipping more distinctly (as in *Fig.* 11b) there is a greater tendency for the ground water to flow towards S, and a more considerable spring is found at that place. Probably the greater

number of springs in England are of this simple type. They tend to dry up during or after dry spells if the area from which they derive their supplies is small.

Landslips. The conditions which give rise to springs of the types illustrated above often lead to the slipping of masses of hillsides and cliffs in the form of *landslips*. In *Fig.* 12, for example, the top of the clay near S is kept wet (and therefore probably slippery) by the constant flow of water; it is like a highly lubricated surface and facilitates the slipping of the overlying rocks. Where these latter are strongly jointed, so that the outer portion tends to break away from that behind, there is still further prospect of slipping.

Frequently landslips in some of the valleys of the South Wales coalfield result from such conditions. Most of the hills are formed of sandstone, while the valleys are

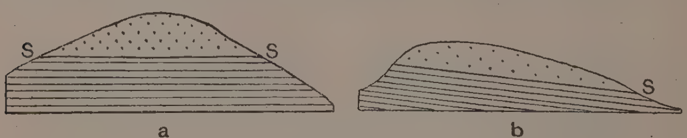


FIG. 11. Diagrams to illustrate the occurrence of springs. (S.)

occupied by shales and clays, and when the rocks along a steep valley side are dipping into the valley there is a strong tendency to slipping; great scars on the hillsides and masses of tumbled rock below show the extent of former slips. It will be realised that when the rocks are dipping into the hills (as on the opposite side of the valley in *Fig.* 12) there is little tendency for such slips.

Landslips are also commonly caused by similar conditions around our coasts, where steep cliffs are cut in rocks of which the uppermost are permeable and the lower impermeable, and where the dip is seawards. The classic landslip at Axmouth, in Dorset, which occurred in 1839, left a scar half a mile long. More recently there have been several landslips along the southern coast of the Isle of Wight, where the Undercliff road has repeatedly suffered from slips.

Where a railway or road-cutting is made through beds which dip into the cutting there is a similar danger of slipping, and one side of the cutting, at least, is usually made at an angle near that of the dip in order to prevent it.

The Work of Ground Water. Apart from its geological action in promoting landslips, most of the work done by ground water is of a chemical nature. It dissolves mineral matter, and so produces chemical alteration of other minerals; the minerals it carries in solution may be deposited in various positions underground.

The solvent action of ground water is illustrated by the composition of spring water. In limestone regions the water is usually very "hard," owing to the presence of bicarbonate of lime. This has been formed by the solution of calcium carbonate in water containing carbon dioxide.

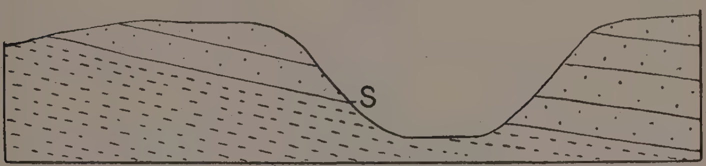


FIG. 12. Section of a valley to show location of landslips; dots, sandstone; dashes, clay.

It is broken up again easily when the water is heated, the calcium carbonate then being deposited; it forms the "fur" which lines the kettle and chokes pipes of boilers. Owing to the ease with which this type of hardness is removed from water it is called "temporary hardness." In other regions common salt, iron compounds, and other materials may be dissolved in spring water; their amounts are mostly small, but the water cannot usually be freed from them except by distillation, so that they are said to cause "permanent" hardness. Occasionally these materials are present in some quantity, giving the water a characteristic taste and in some cases leading to its use for medicinal purposes, as at Harrogate, Bath and other "spas." Iron compounds give to the water an inky taste, and where much iron is present in spring water (in *chalybeate* or ferruginous

springs) the stones over which the water flows often become coated with a reddish-yellow deposit.

An illustration of the work of ground water is to be found in the *cementation* of rocks. Most newly-formed sediments are loose and incoherent, and many of the sedimentary rocks formed from such materials owe their hardness to the fact that ground water has introduced cementing material as a kind of mortar between the grains. Calcium carbonate is commonly met with as a cement in sandstones, and in view of the comparative ease with which it is dissolved by water containing carbon dioxide, it is not surprising to find that it has been carried in solution and deposited in various places into which the water has found its way. The occurrence of other minerals as cementing material (notably of the presence of quartz binding together certain sandstones) is more unexpected, for quartz is ordinarily almost insoluble in water. It has to be remembered, however, that many minerals which are virtually insoluble under laboratory conditions appear to have been soluble at depths in the earth's crust, where high temperatures or pressure may have led to different conditions; it is also important to realise that the removal of some almost insoluble materials in solution may have occupied very long periods of time, and that changes which would be too slight to affect a laboratory experiment may have been continued underground for so long that the results are enormous.

Formation of Mineral Veins. Another aspect of the work of ground water is seen in the formation of some mineral veins. By no means all mineral veins have been formed in this way, but there are many veins in which the minerals may be regarded as having been simply deposited from solution in a narrow cavity, such as in the joints of some rocks. The veins of calcite found in many limestones are of this character, while veins containing quartz and other minerals also occur (*Fig.* 13).

There is another type of mineral deposit which was formed by ground water, not in a pre-existing hole or cavity, but where there was no previous opening. In this type of deposit it can only be supposed that the ground

water, carrying one mineral in solution, made a kind of exchange with some rock with which it came into contact, depositing a particle of the mineral it had carried and taking up a particle of some mineral from the rock; such mineral deposits have been formed by the replacement of the minerals originally present. Some iron ores occurring in limestones have been formed in this way.

Limestone Areas. The work of ground water is most strikingly shown in many of the features of limestone regions. Owing to the relative ease with which the calcium carbonate of limestone dissolves in water containing carbon dioxide, as we have already seen, areas made up of thick

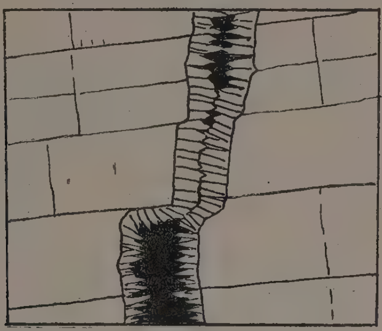


FIG. 13. Vein. Crystals of calcite lining a crevice in limestone; in some cases another mineral may subsequently have filled the spaces shown black.

masses of limestone tend to become areas of underground drainage, in which the streams find courses below the surface and develop systems of caverns, largely by dissolving the limestones.

Massive limestones occupy wide areas in North-West Yorkshire, the Peak of Derbyshire, the Mendip Hills and Gower (South Wales) and similar features are shown in all of them. In many parts, especially on the uplands, the limestones carry very little soil: this is explained by the fact

that many of the limestones consist of almost pure calcium carbonate, which dissolves leaving practically no residue of insoluble material. In some places in Yorkshire (notably on the high ground below Ingleborough) the limestone forms bare white pavements, cut by irregular little chasms representing joints enlarged by the solvent action of rain water: such deeply channelled surfaces are known as *clints* or *grikes* (*Fig.* 14).

In these regions of massive limestone there are few surface streams, but dry valleys and gorges, sometimes with great steps representing waterfalls which have been left dry, mark the courses of former rivers. The Cheddar Gorge in the Mendips, Bishopston valley in Gower, and Malham

FIG. 14. Grikes, Chapel-le-Dale, Yorks.

Gorge in Yorkshire, are examples of valleys which are dry for a great part of their lengths; in the last-named gorge the position of a waterfall formerly 300 feet high is now marked by a steep limestone cliff over which no water flows. The sides of these gorges are frequently straight and almost perpendicular, for the rocks have broken away along strong joint planes.

In the areas mentioned above there are numerous places where streams can be seen to disappear underground. In Burrington Combe in the Mendips, for example, the streams which occupy their little valleys in a normal way as they cross country made up of sandstone and shale disappear

immediately they reach the limestone country. In many cases the streams disappear into a conspicuous hole or cavern, such as those which are frequent in North-West Yorkshire. A well-known example, the largest in England, is Gable Pot on Leck Fell in Lancashire; this is 450 feet in circumference and has a depth of 115 feet, but others on the slopes of Ingleborough, though of smaller extent, are considerably deeper. These *swallow-holes* may open into vast systems of caverns, their directions being determined by major joints. Gaping Gill, under Ingleborough, is a pot-hole 365 feet deep which opens into a great underground chamber 480 feet long, 80 feet wide and 110 feet high.

The growth of a cavern situated not too far below an old dry valley may lead ultimately to the collapse of the roof and so to the formation of a gorge: Gordale in Yorkshire, one of the finest limestone gorges in the country, probably represents a cavern of which the roof has thus fallen in. There are other cases where streams have deserted one cavern and made another at a lower level, but of course this is only possible when there is a great thickness of limestone, for the presence of clays or other impervious rocks below the base of the limestone necessarily limits the development of deeper channels.

When all the drainage passes directly underground the rate at which the land surface is lowered is greatly reduced, for the ordinary effects of river denudation are practically excluded. Thus, apart from such solution of the surface as results from the action of rain water, a limestone area resists denudation as compared with neighbouring areas made of other rock. Consequently many limestone regions stand out as uplands (Mendips, the Peak District), and their surface topography undergoes relatively little modification over long periods; even a comparatively soft rock like the Chalk resists denudation and gives rise to high ground.

The water in limestone regions is highly charged with calcium bicarbonate, and when it flows out as a spring any slight evaporation leads to the precipitation of calcium carbonate. This frequently is found spreading in irregular deposits on hillsides, encrusting leaves and other objects; these

deposits are known as *travertine* or calcareous *tufa*. Some springs are so overcharged with calcium carbonate that articles placed in them soon become coated; they are spoken of as petrifying wells, and such things as baskets and bird's nests are placed in them to be "petrified" (it should be noted that what occurs is not true *petrifaction*, or turning into stone, but merely the coating of the article without any other alteration of its character). There are wells of this kind at Matlock in Derbyshire.

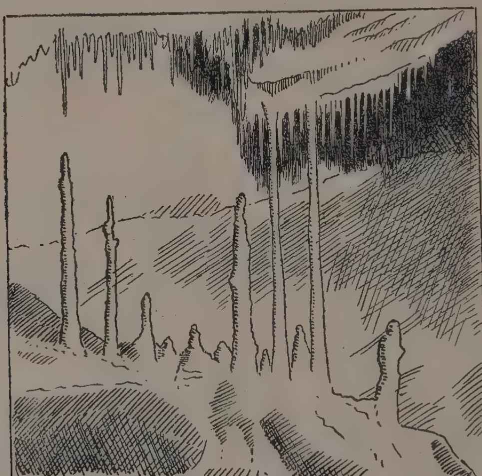


FIG. 15. Stalagmites and Stalactites in a Mendip cave.

The deposition of calcium carbonate also occurs in many caves (especially in caves through which water is dripping to join a stream in a lower cave), and here the deposits often assume peculiar forms. In many cases long pendent columns (looking much like icicles) hang from the roof of the cave, while others, rather similar or perhaps more stumpy, stand up from the floor, the two structures sometimes meeting to form pillars (*Fig*. 15). The hanging structures, known as *stalactites*, mostly have a fairly regular concentric structure, and there is usually a minute open-

ing down the middle. They have been formed where drops of water fall slowly from a crevice in the cave roof, and where each drop hangs long enough to permit of some evaporation, with deposition of some calcium carbonate, before the next one pushes it off. The *stalagmites,* which grow up from the floor, represent the deposit formed by the evaporation, partial or complete, of the fallen drops. It is obvious that if there is a real flow of water from the crevice and no time elapses for precipitation of the calcium carbonate, these structures will not form. They must therefore grow very slowly, but slender stalactites may be formed in a few years; they are sometimes seen under railway arches built of limestone where water has dripped slowly through the stones.

Besides these more regular deposits, many caves have irregular masses of travertine left on the sides and floor. Sometimes these and the stalactites and stalagmites are coloured by other mineral matter (such as red iron oxide), and they may form fantastic patterns of great beauty, as in the caves at Cheddar.

SUGGESTIONS FOR PRACTICAL WORK

Comparisons of the angles of rest of various fragmental materials (such as sand, gravel, limestone chippings).

Evaporate to dryness samples of spring water and show the varying amounts of dissolved solids. (Students with sufficient knowledge of chemistry may also compare the solids from different waters.)

Simple determinations of the porosity of sandstone, chalk, etc., by finding the weight of water absorbed by known weights of dried samples; experiments to show the rate of passage of water through different rocks.

Construction of models to illustrate springs, made with clay and sand.

QUESTIONS

1. Discuss the part which water plays in the disintegration of rock masses. (C.W.B., 1935.)
2. Describe some of the processes that lead to the weathering of rocks. (C.W.B., 1934.)
3. Compare the effectiveness of the various weathering agents in our climate and in desert regions.
4. Explain how springs are caused and why they are rare in certain districts. (C.W.B.Hr., 1933.)
5. Give a series of diagrams to show the conditions under which landslips are likely to occur.
6. Give an account of the type of scenery you would expect to find in a limestone district. (C.W.B., 1935.)

CHAPTER III

THE GEOLOGICAL WORK OF RIVERS AND STREAMS

The Transporting of Material. The observation of local rivers and streams affords a convenient basis for studying the geological work done by running water. The movement of boulders and pebbles by torrents or of sand and mud by more sluggish streams, can readily be observed, and there is little difficulty in demonstrating that these agents do a great deal of transporting. This work is done by virtue of the energy possessed by running water.

It is obvious that the size of the particles carried depends to a great extent on the velocity of the current; a torrent in flood may be seen to move enormous blocks, but these are left standing on its bed at normal times.

The amount of solid material which can be transported by a stream of given volume and velocity is called its *load:* if the speed of the stream is checked some of the material is deposited. The total weight of material moved by a stream also depends, however, on the fineness or coarseness of the particles which are present; clearly, a stream may more easily move a number of fine particles than one large block with the same total weight.

It is interesting to determine very approximately the speeds of various streams by noting the time taken by small floating objects to pass over a measured distance; this will not give a strictly accurate result, for the water at the surface in midstream moves more rapidly than that which is hindered by the sides, but it gives a useful indication of the velocity. Many torrents flow at 10 miles or more per hour; some large rivers flow at less than two or three miles per hour.

Material is carried by rivers in three ways: large particles (sand, pebbles or boulders, according to the velocity of the streams) are rolled along the bed; finer particles are carried in the body of the water, only rarely touching the bottom, and this material is said to be carried in suspension. Some material also is carried in solution; this, of course, consists chiefly of soluble salts.

A rough idea of the total quantity transported annually by various rivers in these different ways has been obtained by making regular observations. The figures for the Mississippi are very impressive and may be mentioned here: this river carries over 400 million tons of material per annum, of which more than a quarter is in solution, and nine-tenths of the rest is in suspension. These figures may not mean much until we translate them into something we can appreciate; for example, if we had to accomplish the same amount of work by railway trains we should need a thousand daily trains each of seventy 20-ton trucks, that is over forty long trains per hour. This amount of material is, of course, being obtained from various parts of the Mississippi basin. If we assume that it has been taken evenly from over the whole of the basin the rate of removal is sufficient to lower the area by one foot in about 3,000 years: it has not been collected at all evenly, so that some areas are being lowered at a greater rate. The English rivers afford evidence that this country is being lowered at a rate rather smaller than that shown by the Mississippi. This gradual lowering of the land by the transporting seawards of vast quantities of material is probably the most important aspect of the work of rivers.

Corrasion. Much of the material transported by rivers consists of the products of weathering, but not all has been derived in this way, for some is the direct result of river work. The material rolled along the bed enables the river *to corrade* or wear it. The pebbles or other particles are the tools with which the river works; they strike the bottom or sides of the channel, and ultimately lead to the breaking away of fragments of rock, large or small, which themselves become part of the load of the stream. This process,

of course, is closely linked up with transportation, and both are largely dependent on the energy of the stream.

Gradient of a River's Bed. If you live in a mountainous region, such as the Lake District or North Wales, you will know that many streams which rise high on the mountain sides descend through a thousand feet in a mile or less from their sources. On the other hand, some English rivers do not fall more than a hundred feet in the last hundred miles of their courses. The gradient down which a mountain torrent falls may be 1 in 5, or even steeper; the gradient of a river flowing in a plain may be only 1 in 5,000. It will be apparent that the velocity of water flowing on the steeper gradient will be greater than that on the gentler gradient.

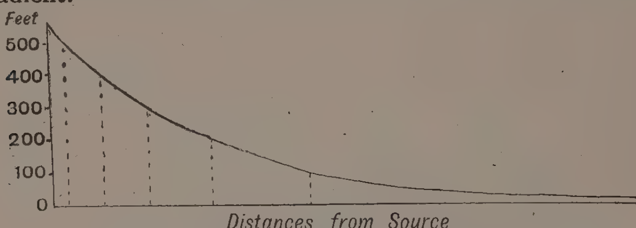


FIG. 16. Diagram of a thalweg of a river. Vertical scale much exaggerated.

Following a mountain stream from Wales or the Lake District, however, we should find that the gradient of its bed gradually became gentler as it left the mountains, and that the stream (united perhaps with other streams) finally became a river flowing across a plain. In other words, the gradient of a river's bed changes from source to mouth; in general (but with important exceptions) the gradient is steep near the source, and gradually becomes gentler towards the mouth. It is a useful exercise to examine contour maps showing rivers and streams, and to measure the distance between successive hundred-foot contours along the courses of selected streams. These distances may then be plotted graphically (with an exaggerated vertical scale), as shown in *Fig.* 16. The graph is a concave curve of

erosion or the *gradient curve* of the river, for it shows the changes in the gradient of its bed from place to place. The usual term for such a gradient curve is a German word, *thalweg*.

If a stream began to flow down an irregular slope where no stream had flowed before, its gradient curve might be quite uneven or complicated, and possibly many streams originally had such gradient-curves. The effect of the work of the stream in such a case, however, would be to carve or corrade the bed when the slopes were steep, and to deposit material where the slopes were gentler, so that the thalweg finally became a smooth simple curve. A river which has so simplified its course as to make the gradient curve comparable with that in *Fig.* 16 is said to have *graded* its bed. This is the form towards which all thalwegs are tending, although certain factors may tend to delay the development of the perfectly graded curve.

FIG. 17. Gorge and pot-hole showing vertical erosion by a torrent. Devil's Bridge, near Aberystwyth.

Characteristics of a Mountain Stream. A stream in an upland region, flowing over a steep gradient, is often something of a torrent, a swift current of clear water, rushing over a boulder bed or a bare rocky bed probably with many waterfalls and rapids. Such a stream will usually be found in a deep valley, perhaps in a gorge, with steep sides in places. This is easily explained when it is remembered that the powerful stream transports heavy boulders and that corrasion of the bed consequently is very pronounced; in other words, a tendency to cut the river bed vertically and to deepen the channel is characteristic of any

torrent or upland stream, and this rapid excavation leads to the formation of a gorge.

The vertical cutting is brought about in several ways, partly by the grinding and wearing action of the boulders on the bed, in some cases by pot-hole formation, and in others by the recession of waterfalls. *Pot-holes* are more or less circular holes which are formed on a rocky stream-bed by the swirling action of pebbles or boulders that have become trapped in crevices or hollows (*Fig.* 17). As adjacent

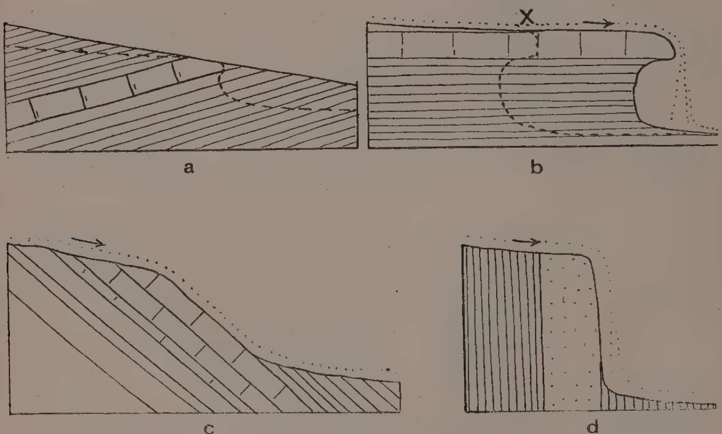


FIG. 18. Diagrams to show the character of some waterfalls. a, rocks dipping up stream; b, rocks horizontal (X shows a position reached during recession of the fall); c, rocks dipping steeply downstream, with fall over bedding plane; d, rocks vertical.

pot-holes become enlarged by the continued swirling of the boulders they eventually become joined and result in a general lowering of the river bed at that place.

Waterfalls. Waterfalls need more consideration. A waterfall often occurs in a stream-bed where the water passes over a harder band of rock (such as a sandstone or limestone, or in some cases an igneous rock) which occurs between beds of softer rock (such as clay or shale). The

fall results from the greater ease with which the river can carve down its bed in the softer material. Consider the case shown in *Fig.* 18a; here we may suppose first that a stream flows from left to right down a uniform slope composed of shale with a bed of limestone. After a while the vertical cutting in the river bed will probably have brought its position down to that shown by the dotted line, little cutting having taken place where the limestone is present, much more having occurred below the limestone; the bed of the stream above the fall is only cut down to just above the level of the limestone, for obviously the stream is unable to cut down so deeply as to form a basin out of which it must flow uphill: the rate of cutting down of the limestone thus controls the rate of cutting in the softer rocks immediately above.

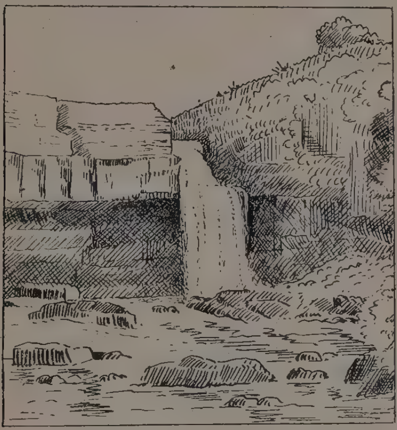


FIG. 19. Waterfall over band of igneous rock, High Force, Teesdale.

Many waterfalls have this structure; the famous High Force in Teesdale has a band of basalt over softer beds (*Fig.* 19); many of the falls of the Yorkshire dales and those of the Neath valley in South Wales have sandstones over shales; Niagara is formed by limestones resting on shales. A waterfall of this kind is an expression of the stream's temporary failure to complete the grading of its bed owing to the different resistances of various rocks.

As the water falls over the ledge of harder rock it creates such a swirl as leads to the rapid wearing of the softer rock underneath the ledge, so that the latter is undercut (*Fig.* 18a,b). In many falls it is quite possible to walk behind the water. The gradual undermining of the

hard band eventually causes the latter to break away (mostly along a joint plane), and then the whole process is repeated. One result of these changes is that the position of the waterfall slowly recedes or moves upstream. As it does so, the stream-bed is, of course, lowered by the amount of the height of the fall. Consequently the waterfall is situated at the head of a gorge while the length of the gorge shows the distance through which the fall has receded. For

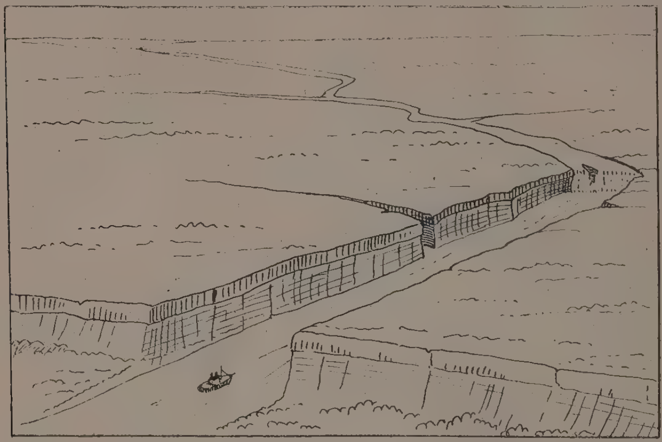


FIG. 20. Diagram to show the gorge below Niagara Falls; the falls were once at the edge of the plateau, the gorge being formed as they receded.

example, the gorge into which the Niagara falls is some seven miles long, and it is probable that at one stage the falls were much further downstream (*Fig.* 20), seven miles away from their present position.

In *Fig.* 18b the rocks shown are nearly horizontal, but somewhat similar conditions occur when the rocks are dipping not too steeply upstream (*Fig.* 18a). When the rock beds are vertical a waterfall may be caused by a hard band but the fall will not recede upstream (*Fig.* 18d). On the other hand, where rocks are dipping downstream they usually form rapids rather than falls, though if the dip

downstream is steep a bedding plane may form the steep face of the fall (*Fig.* 18c). It may be remarked here that some waterfalls have been formed in other ways than these: reference will be made to them later.

Characteristics of a River in a Plain. In the lower part of its valley a river has only a gentle gradient, and it flows slowly. It is unable to do much vertical cutting, for its bed is already not far from sea level, and of course it cannot cut down below sea level. A river in its plain portion has reached or nearly reached its *base level,* below which it cannot carve vertically any further; its base level

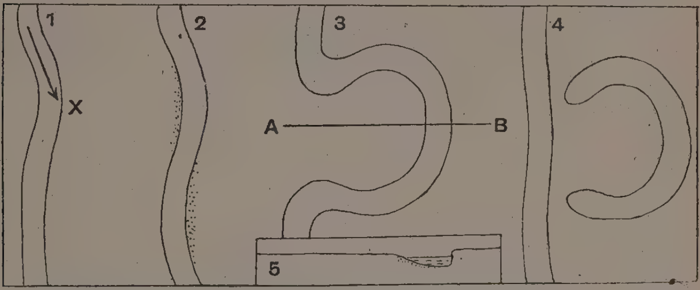


FIG. 21. Development of meanders in a mature river. (4) shows ox-bow lake; (5) is a section across (3) from A to B.

is not quite sea level, for a river must have some slope to its bed if it is to flow at all. In general, therefore, a river in its seaward portion is unable to cut vertically, and if it has lost that power for some time its valley will show none of those features (gorges, pot-holes, waterfalls) which characterise the mountain stream.

In the plains, rivers tend to cut horizontally rather than vertically: instead of deepening their valleys they make them wider. An important factor in this valley widening is found in the tendency of such lowland streams to form winding or meandering courses. Nearly every stream which has reached base level tends to meander. It is easy to see how this occurs in a stream which has no power to cut a deep and simpler channel. When once some slight bend is intro-

duced, perhaps by the slipping in of a part of the bank, the water has not the power to remove it and tends to be swung out of its course and to impinge somewhat on the opposite bank (X, *Fig.* 21). As a result this part of the bank is worn away more rapidly, and the slight concavity of the bank is increased. Thus, once a slight bend is developed, it inevitably grows and ultimately becomes a meander. While the *concave* parts of the bank are being eroded, the material tends to be carried downstream and deposited on the *convex* parts. It is often found that the concave bank is steep or even undercut, while the convex bank is gently sloping (see *Fig.* 21, 5).

The size of the meanders depends on the volume of the stream; a large river has meanders a mile or more across, a small stream may have several meanders in a single meadow.

As a meander develops it may form an almost complete loop, which is ultimately broken by the river (possibly in a time of flood) breaking over the narrow neck and "short-circuiting" the course. For a time a curved lake marks the position of the old meander left derelict on the plain. Such lakes are known variously as *oxbow, loop* or *mort lakes*. Like all lakes, they tend to get filled with sediment in time, but may remain then as slender swampy depressions.

Meanders not only grow in size in this way but they also tend to move downstream, for the maximum erosion occurs further downstream than the greatest concavity of each bend (see *Fig.* 21).

The river plain in which meanders are formed is often made up of sands and gravels brought down by the river in time of flood. The *alluvium* or alluvial material thus forms the flood plain of the river. Beneath it are the solid rocks which rise to form the higher ground on either side of the flood plain (*Fig.* 22). The plain itself is liable to flood, and since it is practically level the floods inundate it almost completely. It is a fertile belt, usually of meadow-land, and is rarely built on because of its liability to flood and the dampness of its position.

It will be apparent from what has been said about the shifting of the meanders that any position occupied by the river in the flood plain, at one side or the other or near the middle, is quite temporary, and it must be borne in mind that the river at one time or another occupied each part of the plain. Sometimes a concave part of a meander is right at the edge of the flood plain, and the river is then cutting into the solid rocks, and so widening the flood plain (*Fig.* 22b). In this way flood plains have been formed and may be continuously extended.

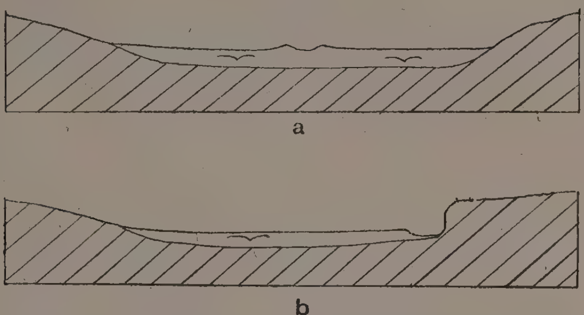


FIG. 22. Sections across the alluvial plain of a mature river. In b, the river is at the extreme edge of the plain and is cutting a cliff in solid rocks.

The Forms of River Valleys. It has already been emphasised that the valley of an upland stream which is actively cutting downwards tends to be gorge-like, while the valley of a river nearing the sea tends to be wide with a flat alluvial plain. Other factors cause some modifications of these valley shapes. One is the relative rate of river erosion and of weathering in the area. For instance, if a gorge is cut by very rapid vertical corrasion its sides will be steep, but if it is cut more slowly and weathering is particularly active the steepness may be greatly reduced (*Fig.* 23c). The shapes of many valleys, seen in cross section, show different phases of this balance between river erosion and weathering.

In regions with dry climates the absence of moisture modifies the effects of weathering, and gorges often tend to remain steep-sided. The most impressive example is the Grand Cañon of the Colorado, where a valley over a mile deep has been carved by an active river flowing through a desert region, in which the effects of rain are practically excluded.

Another equally important factor controlling the shape of a valley in cross section is the nature of the rock in which it is cut. The resistance to erosion and the disposition of bedding planes and joints profoundly affect the valley form. If the rock is tough and weathers slowly, the sides will remain steep much longer than they would if the valley were cut in a clay or soft sand. Thus the shape of any valley

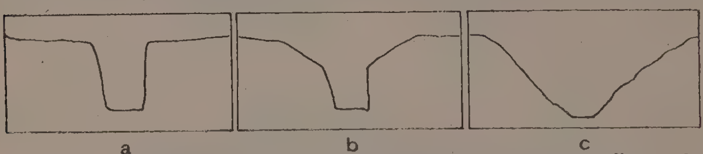


FIG. 23. Sections of different gorges, to show the effect of weathering on a steep sided gorge (a).

may alter from point to point as the course of the river passes over different groups of rock. The *gaps* in the Chalk hills (the North Downs and the Chilterns) which enclose the London Basin illustrate this point. For example, the Thames both above and below Goring gap occupies a wide valley with gently sloping sides, cut in rocks with little resistance to weathering, but the steeper sides at Goring are cut in the more resistant Chalk. The twin gaps in the Chalk hills at Corfe (Dorset) are similar in many ways (*Fig.* 24).

Alluvial Deposits. The material transported by a river or stream may be deposited when the speed is checked. The coarser material is first to be dropped, the finest material the last. River-borne deposits thus tend to be sorted according to the size of their grains.

A tributary with a steep gradient on joining a main stream which has a gentler gradient drops much of its

material at the confluence, and a triangular mass may spread out fan-wise from the mouth of the tributary valley. Such alluvial fans, raised above the general level of the alluvial plain of the main stream, are well seen on either side of the Vale of Neath in South Wales.

The chief characters of the alluvial plain have already been described. One other feature may be noted here. Although in time of flood the water may cover the whole plain, the greatest flow of water is along the river channel. Its banks may thus receive more deposit than the rest of the plain, and so be raised to form *levees* (*Fig.* 22a). A tributary flowing across an alluvial plain may find it difficult to pass across such an embankment, and may flow for some

FIG. 24. Twin gaps in Chalk ridge at Corfe Castle, Dorset.

way alongside the levee before it can make confluence with the main river. The Yazoo flows for some 200 miles along the Mississippi plain before it joins that river. In other cases the tributaries may be held back so effectively by the levees that lakes are formed by them on the flood plain, as in the tributaries of the Red River of Louisiana.

When a river flows through a lake it loses practically all its transported material (except, of course, that in solution). The rivers entering a lake may be laden with sediment, but the water flowing from it is clear as crystal: the water of the Rhone as it enters Lake Geneva, charged with great quantities of material from the melting glaciers, is in sharp contrast with the clear river which emerges at the western end, there to join the muddy waters of the Arve which have not been cleansed by passage through a lake.

The extensive delta at the head of Lake Geneva testifies to the amount of sediment which has been brought down in this way; it forms a great flat and fertile stretch very different in aspect from the mountain lands around.

Similar features are shown in most British lakes. There are deltas at the head of Windermere and Derwentwater. When a main valley holding a lake is joined by a tributary at some point along the lake the resulting delta juts out into the lake and may in time cut the lake into two. This has happened in Keswick where Derwentwater and Bassenthwaite, which formerly were united in one large lake, are separated by the combined deltas of the Greta and Newlands Beck (*Figs*. 25, 26); in another Lake District valley, Buttermere is similarly separated from Crummock Water; and in Switzerland, Interlaken stands on a delta between Lakes Thun and Brienz (*Fig*. 26).

The deltas formed at the mouths of rivers afford further illustration of river-borne material. They are formed chiefly of clays, sands and gravels which are stratified. The rate of extension of such deltas is often rapid. The Po has extended its delta 14 miles beyond Adria, formerly a port. The Ganges and Brahmaputra delta has an area approximately equal to that of England and Wales, while the delta of the Mississippi is advancing a mile every 16 years. Deltas are not formed at river mouths where powerful tidal or other currents sweep away the river-borne sediment.

Youth and Maturity of a River. It is necessary to consider briefly the history of a river. In the case of which the gradient curve is illustrated in *Fig*. 16, we have already seen that the stream is actively engaged in vertical cutting near its source, and has lost the power to cut vertically towards its mouth, where it is approximately at base-level. Now suppose that this particular stream continues to cut vertically in its upper portion, it is obvious that there also it must eventually approach base-level, and vertical cutting will cease. Conversely, we may perhaps suppose that formerly the stream was actively engaged in vertical erosion in those parts of its course where base-level has already been reached. In short, in the course of its history a stream

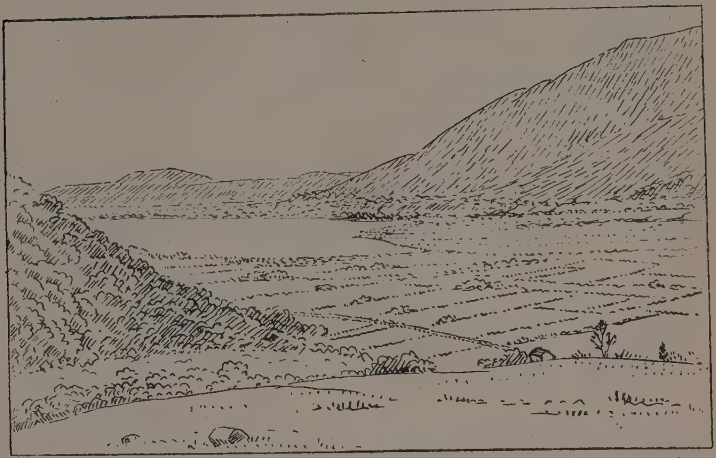


FIG. 25. Delta at the head of Bassenthwaite, seen from Whinlatter Pass (Lake District). Skiddaw is seen on the right.

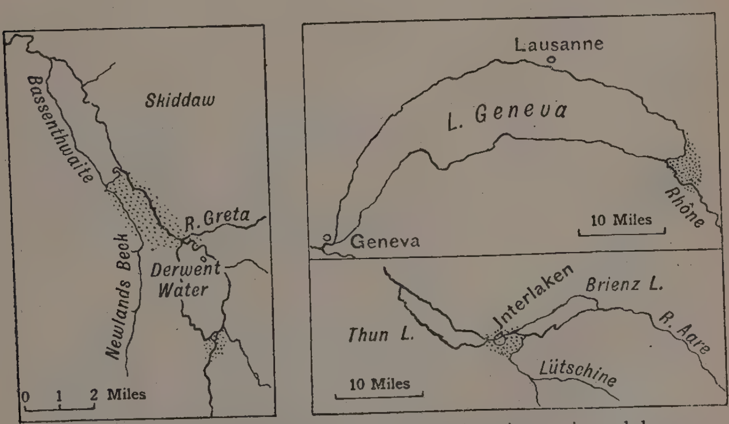


FIG. 26. Maps to show position of deltas in various lakes.

normally begins with vertical cutting and as it becomes graded proceeds to horizontal erosion.

A stream which is cutting vertically may thus be regarded as *immature* or youthful, and as it approaches base-level it becomes *mature*; in any given stream the upper portion is usually immature and the lower portion mature, and in the ordinary course of events the mature part of the stream will gradually extend. Many of the rivers of England—the Thames, the Trent and the Yorkshire Ouse—are mature for a great part of their courses. Many of the rivers of Wales and of Scotland, on the other hand, are immature for much of their length, being mature, if at all, only very near the sea.

Peneplains. If a river continues to flow for a sufficiently long time it thus tends to reduce its bed to base-level. Its tributaries and perhaps also the neighbouring rivers and their tributaries attain a similar condition. As all these rivers widen their valleys the whole area is gradually brought to something near a plain; it is not absolutely level, and isolated hills probably stand out from it here and there. Such an area of lowered land is known as a *peneplain* (literally, *almost* a plain). In such an area the rivers meander slowly in wide alluvial plains, and their maturity shows that they have been flowing for a very long period.

The Struggle for Existence among Streams. A stream may undergo other changes in the course of its history besides gradually attaining maturity. One of the most important of these is that it may grow in length. This occurs at the source, for as the valley there is deepened by vertical cutting, there is a tendency for more water to run down into it from the ground above the source. So the valley is extended and the source is pushed farther inland. This headward extension of the stream in some cases carries the source into higher ground above the valley head, but ultimately it carries it beyond this into the lower ground of a neighbouring drainage basin. When this occurs, the river which is extending its course may begin to poach on the drainage of another basin, and eventually may divert

streams which formerly flowed in one direction and make them tributaries to itself (*Fig.* 27).

Along the divide or water parting between two rivers or groups of rivers this struggle for extension of basins is continually in progress, and the more active (or more successful) streams capture the others. The largest of our rivers are generally those which have been most successful in this work of robbing their neighbours.

Rejuvenation of a River. So far we have thought in terms of rivers which have been cutting down to a base-level determined by an unchanging position of sea-level. But the sea has not remained always at the same level in relation to the land. We may consider the case where the

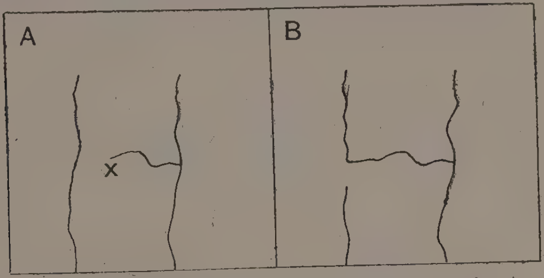


FIG. 27. River Capture. The river at x in A, by headward erosion, has captured the upper portion of the adjacent river in B.

land has been raised (for the result is the same so far as the rivers are concerned if the sea-level falls). Probably Britain has been raised on several occasions since the rivers began to excavate their valleys; some of the reasons for this conclusion will be given later, but at present we are only concerned with the effect on the character of a river's work.

The elevation of land on which rivers have become mature and on which they meander on wide alluvial plains, gives them renewed power to cut vertically down to a new base-level. The rivers thus renew some of their youthful activities, and we may say that such an uplifting of the land causes the *rejuvenation* of the rivers.

One result of such rejuvenation may be that a river with a well-established series of meanders carves its bed deeply and forms a gorge which follows the windings of the old meanders. Such entrenched or *incised meanders* are famous in the River Wye above Chepstow, in the Wear at Durham and in the Moselle above Coblenz. The association of a gorge (characteristic of an immature river) with

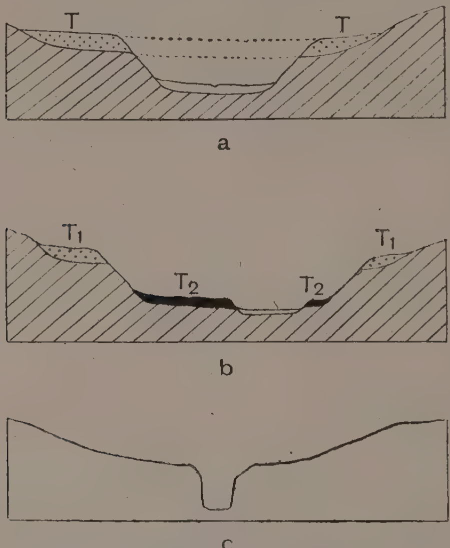


FIG. 28. Sections of valleys of Rejuvenated Rivers. a, b, to show formation of river terraces (T, T1, and T2); c, showing a gorge incised in a mature river valley.

meanders (characteristic of maturity) is a clear indication that something has occurred to disturb the usual sequence of features in river development.

Another sign of rejuvenation is the occurrence of *river terraces*. These are gravel-covered platforms situated at a regular distance above the flood plain of the river, sometimes extending fairly continuously on both sides of the

valley (*Figs.* 28, 29). Their origin is easily explained; a mature river with a wide flood plain has been rejuvenated and has cut a new valley through its alluvial deposits. Often in such a case the river spreads a new deposit of alluvium on its flood plain as it again reaches maturity. The river terraces thus represent the dissected remnants of an old alluvial plain, but since they are sufficiently high above the river they usually differ from the ordinary alluvial tract in being well drained and forming sites which have attracted villages and settlements. In some valleys (*e.g.* the Thames valley) there are several well-marked terraces one above the other, showing that the area was raised on different occasions; in such a case the highest terrace generally (though not always) represents the oldest stage in the de-development of the valley.

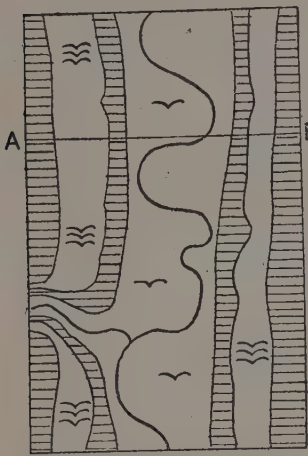


FIG. 29. Map showing river terraces. Fig. 28a, shows a section from A to B.

It will be seen that the river terrace shown in *Fig.* 28a must be the relic of an alluvial plain wider than that of the present time, and many river terraces appear to suggest a degree of base-levelling greater than that shown at present. In the gravels of these old terraces the bones of extinct mammals are sometimes found, together with flint implements used by the pre-historic men who lived when the valleys had only been excavated to this extent.

While in some valleys the river terraces are fairly continuous and symmetrical on both sides of the river, it should be noted that in other cases the terrace gravels are only present in patches, now on one side of the valley and now on the other. As the present alluvial plain grows in width, the terraces become more incomplete.

SUGGESTIONS FOR PRACTICAL WORK

Simple experiments to illustrate the transporting of material and the sorting action of water; a demonstration of "panning."

Evaporation and filtration of stream water to show dissolved and suspended material.

Rather more elaborate experiments to illustrate such problems as delta and meander formation can be devised along the lines described by Prof. A. G. Ogilvie (*Geographical Journal,* lxxxvii, 1936, p. 145).

Construction of gradient curves for selected rivers, using ½-inch or 1 inch Ordnance maps.

Studies of valley forms on such maps; if students are not familiar with contours the drawing of sections across valleys may be extended here, as section drawing is essential at a later stage.

Examination of one-inch geological maps, for examples of alluvial plains and river terraces.

QUESTIONS

1. Describe the features which are characteristic of the various parts of a normal river valley. Give diagrams.
2. Explain the causes which lead to the formation of waterfalls. Describe the character and development of a typical waterfall. (C.W.B.Hr., 1928.)
3. What do you understand by the gradient of a river bed? Show how this may change at various points in the river's course, and explain the effects of the varying gradient on transportation and erosion.
4. Discuss some of the ways in which gorges have been formed.
5. Summarise the effects which will be produced on a mature drainage system by a general uplift of the area.

CHAPTER IV

THE GEOLOGICAL WORK OF ICE

It is easy to make observations on streams and to note their methods of working, but ice cannot be seen at work in this country. The results of ice action are readily observed, however, in Scotland and Wales and Northern England, and it is important to understand glacial phenomena since most of these areas were covered by ice until a comparatively short time ago; in many places the results of ice action are so fresh that they can have undergone scarcely any alteration since the ice disappeared.

It is owing to the recent date of the Great Ice Age in Europe and North America that special attention must be paid to the work of ice. In general ice has not been so important an agent of change as weathering or running water; a glacier must not be thought of as a great gouge churning out a deep trough-like valley at a rate much more rapid than a river is able to work, for the excavation of most of the British valleys which were occupied and enlarged by glaciers had previously been done by rivers.

Snow and Ice Accumulations. A covering of stationary snow or ice does not accomplish any geological work, for it acts to some extent as a protection to the rocks beneath, preserving them from the action of the weather and particularly from the effects of frost. It is only when ice begins to move that it may act as an eroding agent.

Snow remains all the year round on those parts of the mountains which are above the "snow-line." There the amount of snow which falls during a year exceeds the amount which is lost by melting or evaporation; below the snow-line the loss is greater than the total fall. The snow above the snow-line may thus increase in quantity from year

to year, but the excess is removed in two ways, first by sliding rapidly down to below the snow-line in the form of avalanches, and secondly by moving gradually down in the form of glaciers. These may extend great distances below the snow-line, until the rate of melting exceeds the supply of ice moving down.

Valley Glaciers. The glaciers of the Alps, like those of the Himalayas and Rocky Mountains, occupy valleys, and may be known as valley glaciers, for they are simply rivers of ice, their shapes being closely controlled by the form of the valley in which they flow. Near their lower ends many of these glaciers appear dirty and unimpressive, but much of the ice is a clear green, especially when seen in cracks and crevasses. The surface of such a glacier is often very irregular and progress along it may be very

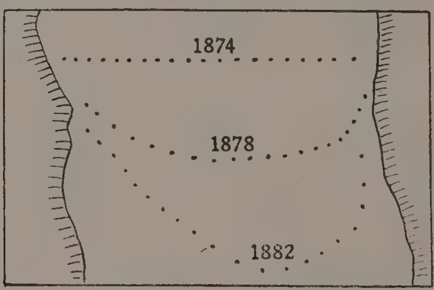


FIG. 30. Diagram to illustrate the movement of ice by a line of stakes.

difficult, especially where crevasses are frequent. These mostly extend across the glacier, and are most marked where ice descends rapidly over a steep place in the valley, the surface being then much broken up, but as the ice passes on to a more regular bed the crevasses often tend to close up again (*Fig.* 32). There are occasionally also longitudinal crevasses extending parallel to the sides of the valley; these are frequently found where the glacier spreads out suddenly to occupy a wide valley.

The movement of Alpine glaciers was measured very simply by placing a row of stakes in a straight line across

the ice and noting their positions in separate years (*Fig.* 30). After a year or two it was found that the stakes formed a marked curve, which became very sharp after eight years, the centre stakes being moved three times the distance of the end ones. The ice in the middle of the glacier thus moves more rapidly than that at the sides. The rate of movement in the Mer de Glace is about 2 feet per day. Some Alaskan glaciers, however, move at 7 feet per day, while Greenland ice has been observed to move more than 60 feet per day.

FIG. 31. Diagram of moraines (medial and lateral).

The surface of the glacier may be littered with blocks and boulders of all sizes which have been broken by frost action from the rocks of the valley sides and have fallen on to the ice. Some of the large blocks stand up above the general surface of the glacier on pedestals of ice, formed because the block has cast a shadow and has thus retarded the melting of the ice immediately beneath it. Much of the material borne on the ice is heaped up in vast irregular moraines, either along the sides of the glacier (*lateral moraines*) or down the middle (*medial moraines*); the lateral moraines, of course, represent material which has fallen

from the sides of the valley, but medial moraines are only found when glaciers from adjoining valleys have coalesced (*Fig.* 31).

Material is carried partly on the surface of the glacier in this way, and partly within the ice itself. For not only does material fall into crevasses and so into the ice, but fragments are picked up by the ice from the rocks over which it passes. The lower part of the ice is thus charged with debris of all degrees of coarseness. Many of the boulders which have been carried along frozen in the base of the ice, show characteristic scratches or striæ where they have been rubbed on one another or on the rocky floor.

At the termination of many valley glaciers a cave opens out from the bottom of the glacier, from which flows a very turbid stream, consisting of melt water which has found its

FIG. 32. Section along a glacier, showing the development of crevasses.

way by crevasses and under the ice (*Fig.* 33). Great quantities of pebbles and fine mud are carried out by this stream. The mud has been produced mainly by the grinding of the boulders on one another and on the floor of the valley. It differs from the mud carried by ordinary streams, which is principally the result of weathering of rocks and in which the mineral particles have often undergone chemical alteration; glacial mud is really rock flour, formed by crushing rocks but not by their chemical alteration.

When a glacier melts at its termination the material which it has carried both on and within the ice is there dropped; some may be carried away by the glacial stream, the rest forms an irregular deposit of blocks of all sizes. If the termination of the glacier remains in the same place for many years, a great mass of such material may be

formed extending right across the valley like a great dam; this is a *terminal moraine*. If the glacier is shrinking, however, and its termination is thus receding up the valley, the morainic material is spread more evenly on the valley floor. Any considerable terminal moraine thus marks a place where the end of the glacier has remained for some time.

If we follow an Alpine glacier (such as the Mer de Glace or the Aletsch glacier) from its termination up to its highest parts we shall find that as we go upwards the glacier surface ceases to consist of hard clear ice, ultimately becoming coarsely granular ice, called *névé*, formed of grains

FIG. 33. Stream emerging from cave under glacier, Grindelwald, Switzerland.

of snow loosely compacted together. Above this are extensive snowfields which form the source of the glacier, and from which the glacier is fed.

Other Ice Accumulations. The valley glaciers of Switzerland are perhaps the best known to British travellers, but there are many large ice accumulations which call for some notice. In the first place, in Alaska, there are many valley glaciers which extend so far down the valleys that they pass from between the confining hills and spread out on the plains, the ice from one valley in some cases coalescing with that from another to form a wide sheet of ice which completely covers the low ground.

In other regions, such as the Antarctic and Greenland, there are still larger ice masses or *ice sheets,* in which ice buries mountains and valleys alike, completely hiding the original relief under a more or less dome-shaped covering of ice. In the Antarctic the tops of the higher mountains appear above the ice, and in Greenland also some mountain peaks project especially near the borders of the ice sheet: these projecting patches of land are known as *nunataks.* Around them a certain amount of morainic material is found on the ice but otherwise there is little debris on the upper surface of the ice sheet, for obviously there is no way in which it could be supplied. Great quantities of material in the lower part of the ice show to what extent the glaciers erode the rocks over which they pass.

Where ice sheets reach the sea they give rise to icebergs which float away carrying some of the material enclosed in the ice, to deposit it, when they melt, on the sea floor. The shallow seas near Newfoundland are partly due to such deposits.

The Movement of Ice. The actual way in which ice moves is not very easy to understand. It is certainly not correct to suppose that it slides forward bodily over its bed as a solid mass, for it is obvious that it accommodates itself and remoulds its shape to fit the valley as its passes along. On the other hand it is probably incorrect to think of ice behaving simply like pitch or some viscous fluid, for it is much more brittle and rigid, and is essentially crystalline. In the movement of ice it is probable that very small portions are temporarily melted and almost immediately frozen together again, but in slightly different positions. The melting probably results from pressure, for an increase of pressure causes a lowering of the melting point.

This is easily illustrated experimentally by taking two pieces of ice and pressing them together; on relieving the pressure, the two pieces are found to be frozen together. The pressure, by lowering the melting point, causes a thin film of ice to melt which freezes again when the pressure is reduced, cementing the blocks. This phenomenon is known as *regelation,* and it is that which causes a handful of snow to harden when compressed into a snowball.

In moving ice it is only necessary to suppose that minute films are melted between the adjacent particles in order to understand how these particles may roll or slide over one another. There may thus be different rates of movement in different parts of the mass, and the glacier is able to adjust itself to the form of its bed, while retaining many of the properties of a solid.

The Work of Ice. In some respects the geological work of ice may be compared with that of running water, for it corrades its bed, transports material and makes new deposits. It will be convenient first to consider the erosive work of ice. The results of this work may be studied in Britain as conveniently as in Switzerland, and they are particularly well seen in Scotland, the Lake District and North Wales.

Glacial Smoothing and Striation. An area over which a glacier has passed is different in many features from an unglaciated region. Scattered irregularly over its surface there are usually large boulders of many types. In upland areas there are considerable expanses of bare rock exposed at the surface, for all the debris resulting from ages of weathering before the advance of the ice has been swept away. The exposed rocks are frequently polished and smoothed, and the surfaces commonly show scratches or *striæ* similar to those found on boulders which have been dragged along in the base of the ice. From these striated rocks it is possible to determine the direction in which the ice was moving, though in some cases a single rock surface may show more than one set of striæ, indicating that it was crossed by ice moving in different directions. The contrast between the ice-smoothed areas and those jagged surfaces immediately above, where the rocks have been shattered by frost action, is very striking.

The projecting masses of rock which stood up in the path of the glacier have been rounded away on the sides facing "upstream," but on the other sides they are usually somewhat craggy and irregular. The advancing ice, with stones embedded in its base, ground away the sides against which it flowed, but as it passed over the obstacle it tended

to pull or pluck away blocks of rock, breaking them away, especially along their joint planes. Such smoothed rocky hillocks are known as *roches moutonnées*. Mostly they form bare masses of rock projecting above the bracken or other vegetation of a glaciated hillside.

Form of a Glaciated Valley. It is commonly said that a river valley is usually V-shaped, while a glaciated valley is U-shaped in section. The V-shaped appearance of many river valleys is due to the intersecting slopes of spurs on either side of the valleys (*Fig.* 36A), which make it im-

FIG. 34. A Glaciated Valley, with a waterfall from a hanging valley. Lauterbrunnen, Switzerland.

possible to see far along them. The main effect of glacial erosion in such a valley is to cut off the ends of the spurs, leaving triangular facets (*Fig.* 36B). The valley then appears more open, and it is possible to see from end to end. The valley section appears U-shaped, for the sides are steepened (*Figs.* 34, 35).

In *Fig.* 36B the U-shape is shown to have been produced merely by truncating the spurs, and the valley has not been deepened by the glacial erosion. Many glaciated val-

leys, however, have been considerably deepened by the ice. Where a valley has been thus deepened it is often found that any tributary valleys which have been less affected by the ice "hang" above the main valley. The tributary streams then fall from the *hanging valleys* by a waterfall. Many of the large Swiss waterfalls have this origin (*Fig.* 34), and numerous falls in this country are due to a similar cause (*e.g.* many falls in the Lake District). It will be noted that waterfalls of this type do not primarily owe their position to a hard rock among softer rocks, as in the case

FIG. 35. A Glaciated Valley, Llanberis Pass, N. Wales.

of many falls referred to in the last chapter: the recession of the fall may, however, leave a gorge at the lower end of the hanging valley, and a harder rock may then determine the position of the receding fall for a long time.

In many valleys one effect of the glaciation has been to intensify any irregularities in the gradient which existed before glaciation; thus while a river tends to grade its bed a glacier in some circumstances may make the gradient curve more complicated. It appears that ice tends to scoop out hollows and to accentuate irregularities of slope, partly by that plucking action mentioned above. Thus many

glaciated valleys are marked by quite considerable "steps" in their profiles, such as that which occurs at Rhaiadr Ogwen, at the head of the Nant Ffrancon Pass (one of the most impressive glaciated valleys in North Wales). On going up this characteristically U-shaped valley it appears that the head has been reached, so steep is the step, but above it the valley continues once more with a moderately sloping floor.

Erosion of Rock Basins. Ice appears to be able to scoop out a basin in the solid rock, but a river cannot do

a b

FIG. 36. a, a valley with everlapping spurs; b, the spurs truncated, forming a U-shaped valley. (No deepening of the valley by glaciation is represented.)

this, for a river is unable to "dig a hole"; a river may carve a valley but it cannot dig its bed below the level of some point over which it has to flow further downstream (except in such small instances as the basins beneath some waterfalls and in pot-holes). A glacier on the other hand can dig a basin of some size, and may dig that basin to a depth below sea level.

The power of ice to achieve these results was doubted for a long time, and it has required much study of glacial basins to demonstrate that there are many hollows in glaciated regions now occupied by lakes, which are completely surrounded on all sides by solid rock. This power

possessed by ice may be understood when it is remembered that when a glacier flows into a hollow it may be forced up the opposite slope by the pressure of the ice behind; ice is sufficiently a solid mass to transmit such pressure.

Rock basins are known in many parts of Scotland; that of Loch Coruisk in Skye is famous; it is about 1½ miles long, and its floor is 100 feet below sea level; Wastwater is a striking rock basin. Glaslyn on Snowdon is another example of a rock basin, this time far above sea level.

Cirque-Formation. A *cirque* is an amphitheatre or armchair-shaped hollow backed by steep cliffs and with a rather level or gently sloping floor, opening out on a hill-side or at the head of a glaciated valley (*Fig.* 37). In the

FIG. 37. A Cirque. Under Craig y Llyn, South Wales.

glaciated areas of Britain there are many cirques, especially on the north-facing slopes of hills, where patches of ice remained longest. Frequently these cirques contain a small lake, occupying a rock basin or held up by a dam consisting of the terminal moraine of the small glacier which last occupied the hollow. In Scotland cirques are known as *corries*.

The origin of cirques is not easily explained, but their occurrence only in glaciated areas makes it certain that they are the results of glaciation. When ice accumulations now occupying such basins (for example in Switzerland) are examined it is usual to find that near the wall of the cirque is a single great curved crevasse. This crevasse, known as

the *Bergschrund,* seems to represent the crack formed by the forward moving ice as it parts from the back wall of the basin: frequently it is wide and very deep, extending to solid rock (*Fig.* 38). It is thought possible that melt waters pass down it in summer, and that the freezing of these waters leads to erosion being at a maximum at the bottom of the crevasse. The wall of the cirque is thus kept steep and is slowly cut back further into the high ground.

Glacial Deposits. The material transported by glaciers was for the most part deposited when the ice melted, though some was carried away by melt water flow-

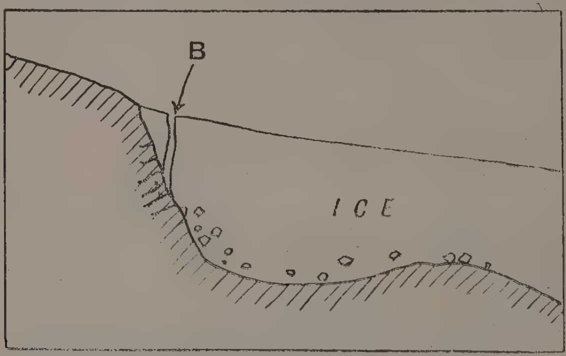


FIG. 38. Diagram to illustrate an ice-filled cirque, with Bergschrund crevasse (B).

ing from the ice margin. Such deposits occur in most parts of Britain lying north of the Bristol Channel and the Thames. They vary from a few feet to over a hundred feet in thickness. The solid rocks may thus be deeply buried, and the glacial deposits thus profoundly influence the nature of the soil. They are known collectively as the "Drift." Geological maps of northern Britain are frequently issued in two editions, known respectively as *Drift* and *Solid* Editions. In the former the glacial deposits are shown, the solid rocks only being indicated where there is no cover of superficial deposits; in the latter, the glacial deposits are omitted and the extent of the "solid" rocks beneath them

is shown. Maps of the former type are most important when questions of soil arise, but for many problems of mining the Solid maps are more useful.

The drift deposits include chiefly boulder clay and gravels. *Boulder clay* is a deposit of unsorted material, consisting of boulders of all sizes embedded in a firm clay. It probably represents material carried in the ice, perhaps mainly in the lower part of the ice, which was deposited when the flow was held up by some obstacle or when the ice finally disappeared. Such deposits, laid down directly by the ice, escaped the sorting effects of water action. The gravels which are often associated with them, on the other hand, frequently show some signs of sorting, and in some cases represent material carried away from the ice margin by melt waters.

Boulder clay is not only distinct from water-laid deposits in its unsorted character, it is also remarkable for its lack of bedding or stratification. In many places it appears as an irregular mass devoid of any of the structural features such as bedding or lamination which are characteristic of nearly all other deposits. The material of which it is composed is also unusual, for the fine clay consists of finely ground rock debris or rock flour (see p. 58). The boulders in the clay are grooved and striated, but they are neither rounded like river-borne stones nor angular like scree material.

Deposits of boulder clay occupy the lower parts of most valleys in upland areas, and many rivers are engaged in re-excavating their old courses. In the lowlands the boulder clay of irregular thickness which was laid down has been cut through by many rivers, and many valleys are being excavated in solid rocks, while patches of boulder clay still remain on the higher ground. These relations of the boulder clay are shown very diagrammatically in *Fig.* 39; it must be emphasised that this only represents the more normal conditions. At the right-hand side of the diagram the boulder clay is shown extending below sea level; there are extensive areas of land on the east coast (in south-east Yorkshire and in Lincolnshire) which were added to England as a result of these glacial deposits.

The upper surface of boulder clay is often irregular owing to the variation in the thickness laid down at different places. It may be marked by low rounded hills enclosing irregular hollows possibly with shallow lakes. Many lakes of this kind are found in north-east Germany; many of those which were formerly present in Britain have been silted up.

Erratics. In glaciated regions large scattered boulders have been left behind by the ice. Many of these boulders are some miles, even hundreds of miles, from their original source; hence they are frequently known as *erratics*. It is possible to decide from whence many such blocks have been carried; for instance in Yorkshire, boulders of a peculiar granite which can only be matched

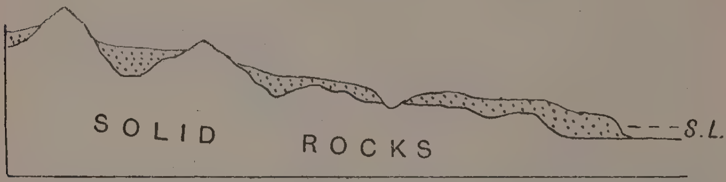


FIG. 39. Diagrammatic section to show relation to Boulder Clay to solid rocks in a mountain area and on plains; on the right the Boulder Clay gives rise to new land. S.L., sea level.

in Shap, Westmorland, are found, while in west and south-west Wales fragments of a rock known only in Ailsa Craig (in the Firth of Clyde) are widespread. The examination of these boulders, and also of those in boulder clays, makes it possible to determine the directions and amounts of movement of the ice-sheets which transported them.

Some of these erratics were left by the ice in very curious positions. They are known as *perched blocks* when they stand, often rather precariously balanced, on steep hillsides or uplands. It must be realised that these enormous blocks, although they are impressive and illustrate forcibly the transporting power of ice, are not to be compared in importance with the great masses of boulder clay which cover extremely wide areas.

Terminal Moraines. Terminal moraines are abundant in glaciated areas in Britain. They generally mark halt-stages during the retreat or disappearance of the valley glaciers, or in other words they occur at places where the ice termination remained for a long time, that is, where the forward movement of the ice just kept pace with the rate of melting. Thus material brought down by the ice over a considerable period was piled up into one great mass, whereas if the ice had been retreating steadily and its termination had changed from year to year, the morainic material would have been more evenly spread out on the valley floor.

Terminal moraines are common in many Pennine valleys, several being present in each valley. They show that in the final disappearance of the ice there were periods when the retreat was fairly rapid, alternating with considerable periods during which little change occurred in the position of the ice termination.

Frequently terminal moraines have acted as natural dams across the valley and have thus given rise to lakes. Many of the small lakes which occupy cirques are held up by crescentic terminal moraines across the front of the cirques: Llyn y Fan Fawr in South Wales, and Bleawater Tarn in the Lake District have been formed in this way. The material forming a terminal moraine consists mainly of loose blocks, however, and it seldom forms a water-tight dam. Many lakes occupying valleys in Scotland, in the Lake District and in Wales are partly due to terminal moraines and partly to irregular deposits of boulder clay. Windermere, Ullswater, and the lakes of Llanberis are all partly due to dams of boulder clay. Numerous other lakes of similar origin which formerly existed have been silted up since the close of the Ice Age.

The Effects of Glaciation on Drainage. In general, rivers reoccupied their old valleys after the ice disappeared, and the drainage of Britain is substantially the same as it was before the coming of the ice sheets. There are, however, some interesting exceptions, and for various reasons certain rivers have taken on courses quite different from those they followed previously.

Most of the changes arose because at a late stage in the glaciation of Britain the lower portions of certain valleys were dammed up by thick ice sheets flowing from more distant uplands, while the higher parts of the same valleys were ice-free. The waters thus held up by ice dams rose in the valleys and formed lakes, which continued to get wider and deeper until the floods escaped either over the ice or over some pass through the hills surrounding the valley. Such a pass may have been cut deeply by the rushing waters to form an *overflow channel,* often a steep-sided gorge. In some cases the river has continued to use this new course after the ice had gone, owing possibly to the presence of a mass of boulder clay forming a further obstruction in the original valley.

One of the most remarkable instances of such diversion of drainage is seen in the course of the Severn. The upper part of that river above Shrewsbury appears to be flowing towards the Irish Sea, and there is little doubt that it took that course before the Ice Age. When its outlet in that direction was blocked by ice, a lake was formed, and this overflowed at Ironbridge, where the water cut the gap through which the Severn now flows; the Severn basin thus consists of separate basins which formerly were quite distinct with rivers running in almost opposite directions; the overflow channel is cut across the divide and makes possible the curious change in the direction of the present Severn.

On a much smaller scale the case of the river Derwent in Yorkshire is equally interesting. This river now rises near the Yorkshire coast and flows *away from the sea* through the Vale of Pickering, to follow a gorge at Malton before joining the Humber. Such a course is so anomalous that it calls for explanation. It is probable that the Vale of Pickering was excavated by a river flowing eastwards to the sea at Filey which was dammed up by ice near the coast to form a wide lake. This overflowed at Malton with the formation of a deep channel by which the river has continued to flow southwards after the ice-dam disappeared.

Such temporary lakes, held up dams of ice, were formed in many valleys, but in most cases the rivers followed their original courses when the ice retreated. It is often possible to determine the former presence of lakes from the heights of the overflows by which their waters escaped. In some cases too beach deposits were formed along the shores of the lakes. The most famous examples of such beaches are in Glen Roy, near Ben Nevis, where at intervals the lake stood at three levels, now at 1,153, 1,077 and 862 feet above the sea. These beaches which make horizontal ledges along the valley sides are known as the Parallel Roads of Glenroy, and have occasioned much discussion. They were once thought to prove that sea level stood much higher during the Ice Age, but it is now clear that they mark lake levels and not sea level.

Similar lakes are sometimes to be observed at present where ice-free lateral valleys are dammed up owing to a thick mass of ice in the main valley; the Marjelen See on the edge of the Aletsch Glacier is one of the best known.

SUGGESTIONS FOR PRACTICAL WORK

Simple experiments on regelation; experiments to show the expansion of water on freezing.

Studies of land forms on ½-inch and 1 inch Ordnance maps of the Lake District, North Wales or the Highlands; recognition of glaciated valleys, cirques, etc., on contoured maps.

QUESTIONS

1. Write an account of the work of ice. Summarise the evidence for the former existence of ice sheets in Britain. (C.W.B.Hr., 1928.)
2. Describe the modifications of scenery brought about by glacial action. (C.W.B.Hr., 1935.)
3. Describe fully the chief types of glacial deposits. By what characters is it possible to distinguish glacial deposits from those laid down in water? (C.W.B., 1927.)
4. Explain fully the various ways in which hanging valleys have been formed.

CHAPTER V

COASTS, SEAS AND OCEANS

Destructive Work of Waves. Everyone who has stood by the rocky sea shore during a storm must have been impressed by the power of the waves. As each mass of water is hurled at the cliffs it is evident that hammer-like blows are being given. The destruction which so frequently results from storms is proof of their power to wear away the land. These facts have long been familiar, and in Britain, where the coast is so easily reached, the waves have been recognised as important agents of erosion. Indeed, there has been some danger of their importance being over-estimated, for the waves are much more noisy and demonstrative than, for example frost or rain, but it has to be remembered that while the waves can only attack the line of the coast, such sub-aerial agents as weathering and rivers are influencing the whole land surface; the total results achieved by these agents are much greater than those produced by marine erosion. The truth of this has been made clear by geologists working in America where, owing to the large area exposed to their influence, sub-aerial agents obviously are able to cause greater changes than result from wave action along the narrow coastal strip.

The battering-ram influence of waves is very considerable, for around the west coast of Britain even in summer the force of each wave is equal to about a third of a ton per square foot, while during a storm it may be three tons per square foot; it has to be remembered, moreover, that these blows are repeated several times every minute. The effective work of waves is much greater than these figures would indicate where the cliff face has crevices and cracks

in which the air is trapped and compressed by each advancing wave; the effect may then regarded as tending to force apart the rocks bounding the cracks. But the waves are most destructive when they are supplied with tools with which to attack the cliffs, in the form of boulders or pebbles which are hurled against the rocks and which greatly increase the rate of erosion. Waves so armed may be compared with those torrents which corrade their beds with the assistance of boulders.

An attack by waves on a coast is rarely successful uniformly at every point, for the waves soon discover the

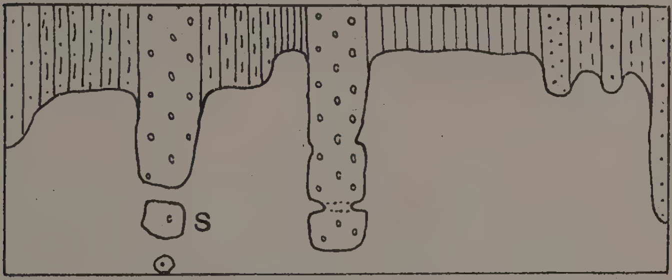


FIG. 40. Map of a coast with vertical beds of sandstone and shale showing differential erosion and formation of a stack at S.

weakest places, and the attack is pushed forward there while little progress is being made elsewhere. The weak places may be caused by softer or more easily eroded rocks occurring amongst harder rocks (*Fig.* 40); thus little bays may be formed, leaving the harder rocks standing out as headlands, as at innumerable places on our coasts. When the rocks are more uniform the weakest places may be the joint planes or bedding planes, and narrow caves may be cut in these. As boulders are swirled round in them the caves may be enlarged until eventually the roof falls in and an inlet is produced. The variety of form in these wave-worn caves and inlets is one of the attractions of a holiday on a rocky coast. When caves on opposite sides of a projecting

headland grow until they meet, they form a tunnel under the headland roofed over by a *natural arch* (as at London Bridge, Torquay). The roof of such an arch will ultimately fall in owing to the continued work of the waves, and thus a portion of the headland may be detached from the mainland (as at S on *Fig.* 41) to form a *stack*.

It is obvious that the work of the waves is mainly confined to the foot of the cliffs, and that it does not extend far above high-tide mark. It is frequently found, therefore, that the cliffs become undercut at their base. Where a horizontal bed of soft rock extends along the base of a cliff it may be very deeply hollowed out, forming a long low cave; ultimately the overhanging rocks break away, probably along a joint plane. If the beds are horizontal and the

FIG. 41. Diagram to show development of caves, natural arch and stacks (S).

joint planes cut them at right angles, a vertical cliff is likely to result (*Figs.* 43a, 45).

When the rocks dip steeply towards the sea the cliffs are not usually vertical, for, as will be seen from *Fig.* 43b, the upper part of the cliff is unstable and tends to slip seawards along the bedding plane; the cliff slope is often determined in such cases by the bedding, as in part of the Gower Coast in South Wales (*Fig.* 44). On the other hand, when the rocks dip inland the cliffs may be correspondingly stable, for there is less tendency for the rocks to fall seawards, especially if joint planes are not conspicuous, and in such cases the cliffs may overhang to a considerable extent (*Fig.* 43c).

Thus the form of the cliff at any place is greatly influenced by the nature of the rocks and their structure. The more resistant rocks tend to form headlands and the soft

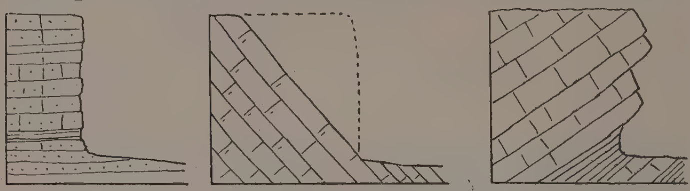
rocks to be worn back to form bays. This is illustrated by the detail of the coast line at many points; St. Bride's Bay in Pembrokeshire is cut mainly in shales, while the headlands which bound it are mostly of hard igneous rocks; Mount's Bay in Cornwall is cut in slates, bounded on the east and west by igneous rocks at Land's End and Lizard. While this tendency to scoop out bays in the more easily eroded rocks is commonly seen, it must not be supposed that all inlets have originated in this way. The narrower inlets especially (such as those of south-west Ireland and western Scotland) are usually due to other causes; a very

FIG. 42. The Needles, Isle of Wight. Chalk Cliffs and Stacks.

little consideration will show that they are not likely to have been formed by violent wave action at their inner ends, for the water inside the inlets is usually very calm. One mode of origin of such narrow inlets is dealt with later (p. 81).

Wherever we see stacks in front of a line of cliffs we may be sure that the waves have been successful in their attack, for at one time the stacks were part of the mainland. It is certain that the waves cut away, at varying rates, the coastal parts of the land. Evidence of such lost lands is abundant in many parts of the coast, and particularly along the Yorkshire coast where the sites of many villages have disappeared owing to wave advance.

As the cliffs are destroyed the waves wear down the coastal tract to a very gently sloping and nearly smooth surface, although some harder bands of rock may project slightly to form reefs. Such a strip may be seen in front of many cliffs when the tide has receded (*Fig.* 46). It will be noticed that the rock beds look as though they have been sawn across to form the level surface; such a tract is known as a *wave-cut platform*, or *bench*. Obviously, as the waves continue their attack the bench is gradually widened (*Fig.* 46, X), so that the stretch of shallow water which the waves must cross before they can reach the cliffs steadily increases. But when the waves reach shallow water they break (as may be observed where waves are entering a shallow bay or crossing a sand bar), and as the bench becomes wider the



a b c

FIG. 43. Diagram showing forms of cliff in relation to geological structure.

a, horizontal beds with vertical joints.
b, limestones dipping seawards.
c, undercut cliff in rocks dipping inland.

more rarely are waves able to cross it with sufficient power to erode the cliffs; perhaps only during very high tides is this possible. The power of the waves thus declines with the increase in width of the bench. A time thus arrives when the cliffs are no longer kept steep by repeated falls of rock; the weather then has more time to soften the profile of the cliff face.

Wave-Worn Material. If we examine at low tide the foreshore under the cliffs of a rocky coast, we find a wave-cut platform, broken here and there by projecting reefs and dotted with shallow pools. Piled up irregularly are patches of boulders and pebbles, lying loosely on the platform and

evidently disturbed by almost every tide. At some places along the base of the cliffs, bigger heaps of rock fragments may be seen, where falls of rock have recently occurred. The newly fallen blocks are mostly angular and are often of large size; the waves quickly sweep away the smaller fragments, and more slowly break up the larger pieces, so that they also are ultimately moved. The boulders are banged against one another and against the cliffs (helping in the further destruction of the latter), and consequently their corners are knocked off and they become smoothed.

The Movement of Beach Material. It is obvious that the breaking up of the cliffs must yield a large quantity of material of this kind, which becomes broken up and smoothed to form pebbles and boulders. It is also evident that not all the material so produced remains on the shore platform. To find larger accumulations it is necessary to look in the bays and small inlets, where there are frequently more or less definite *beaches* composed of this wave-worn material. These contain much material which has been moved along the coast away from the cliffs from which it was broken.

FIG. 44. Three Cliffs Bay, Gower, S. Wales. (Compare *Fig.* 43b.)

The direction in which the beach material is being moved can often be determined by examining certain features of the coast. For instance, where two sides of a bay are formed by cliffs which consist of different rocks,

examination of the boulders on the beach will show that most of them have come from the cliffs at one end of the bay; the direction of movement will thus be obvious. A case of this kind is illustrated in *Fig.* 47, where the cliffs at A are of different character from those at B; the bulk of the pebbles in the beach between these points will consist of material derived from A if the direction of movement is from west to east. If the headland at B projects out into deep water very little of this material derived from A will be carried round into the next bay, which may have a beach in which the pebbles have come chiefly from B.

Another indication of the direction of movement is to be seen in deflected streams. Where beach material is en-

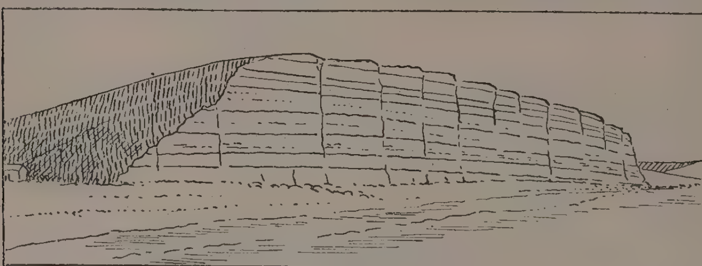


FIG. 45. Vertical cliffs in nearly horizontal rocks, Bridport, Dorset.

croaching on the mouth of a stream it tends to turn it into the direction in which drift is taking place. In some cases a stream flows behind a boulder beach to the extreme limit of the bay where a headland prevents further deflection, when it escapes to the sea under the boulders (*Fig.* 47). But on coasts where there are no headlands the deflection may go on for miles. This is well seen on the coast of East Anglia, especially in the case of the River Alde; this river comes to within a few dozen yards of the sea at Aldeburgh, where its mouth must formerly have been situated, but then flows parallel to the coast just behind a boulder beach for over ten miles before it succeeds in entering the sea.

Across the estuaries of many larger rivers partial barriers consisting of deposits of beach material have been

formed. These *spits* do not always cause a change in the position of the river mouth, for a large river is sufficiently powerful to sweep away the material which impedes its course. The shape of the resulting deposit thus depends on the relative strengths of the river currents and of the currents or waves tending to move material along the coast; after a storm the spit may extend further across the estuary than at other times. The side of a river mouth on which a spit occurs is the direction from which the material is generally moving. Spurn Point at the mouth of the Humber is an excellent example of a spit; it shows the movement of beach material in that area is from north to south.

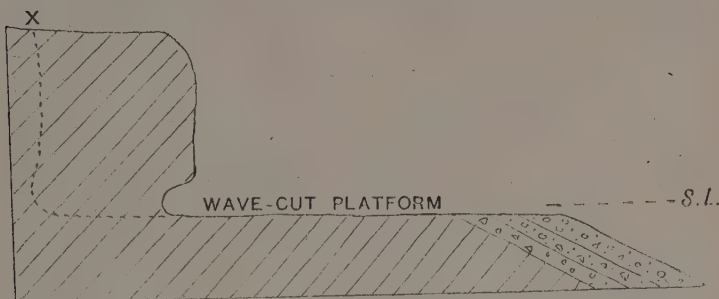


FIG. 46. Section to show relation of cliffs to wave-cut platform. S.L., sea level.

A movement from north to south is commonly found along the east coast of England, while on the south coast it is from west to east and on the west coast from south to north. Probably these directions are determined mostly by the directions of the most severe storms.

The formation of deposits of beach material in this way leads to the addition of new land to some parts of the coast. The work of waves therefore is not wholly destructive, and new land (not at first of very much value) is being built from some of the material worn from the cliffs elsewhere. Moreover, the construction of spits and barriers across the mouths of rivers often causes a reduction in their rate of flow and so leads to the deposition of river-borne material

behind the spits, and thus to the formation of areas of low-lying ground: Romney Marsh has been partly formed in this way, while the Broads of Norfolk are mostly river estuaries which have been obstructed by beach material and which are becoming silted up.

Beach material is important in another way. When it accumulates on a beach it reduces the depth of water at that spot. Now we have already seen that waves cannot cross a wide tract of shallow water and attack the cliffs behind; the presence of abundant beach material may thus render the waves powerless to destroy the cliffs. For this

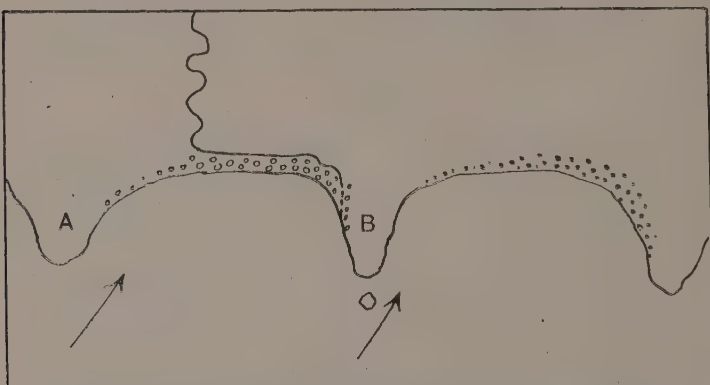


FIG. 47. Map to show the movement of beach material. The arrows show the direction of most important storms.

reason an attempt is often made to encourage the accumulation of beach material, for instance in front of seaside towns, by the erection of wooden or concrete *groynes* running out at right angles to the coast. These hold up the movement of pebbles and shingle and so prevent the waves from reaching the cliffs. The pebbles are thus piled up on one side of a groyne while the beach is much lower for some way on the other side.

The Effects of Changes in the Sea Level. Along many coasts there are indications that the sea has not always been at the same level relatively to the land. There

are evidences that in some places the land has risen (or sea level has fallen), while at others the land has sunk (or sea level has risen). It is not always easy to determine whether a given change is due to the rise of the land or a fall of the sea level, or whether another is due to the sinking of the land or a rising of the sea level, and the ways in which these questions can be settled are not explained here; it is sufficient to remember that in a general way a rise of sea level gives much the same results at any place as the sinking of the land.

It may be wondered how the level of the sea can have been lowered, and one way in which this has been brought about may be noticed here. During the Ice Age much water, which during normal climatic conditions would have flowed by way of rivers into the sea, was "locked up" on the land. The volume of ice covering great areas of the Northern hemisphere at that time was so vast that it resulted in a distinct lowering of sea level; the level rose again as the ice melted and the water was returned into the sea.

A coast of which the lower parts have become submerged, whether by a change in the level of the land or of the sea, is known as a *Coast of Submergence;* a coast which has emerged from beneath the sea, whether by a rise in the land level or a falling of the sea level, is known as a *Coast of Emergence.*

On a coast of submergence the features which used to form the coastal area have been drowned: the submergence of a valley may give rise to an inlet in which all the winding and branching of the valley are retained. Drowned valleys are well seen along the south coast of Devon and Cornwall, as, for instance, in the mouths of the Yealm and Fal; in South Wales the Milford Haven is another example, while many of the deep inlets of south-western Ireland are similarly drowned valleys. The indented coast-lines of the west of Scotland and of Norway also result very largely from submergence, and many sea-lochs and fiords are submerged glaciated valleys. It will be obvious that the pattern of a coast-line of submergence depends primarily on the nature

of the land which has been submerged; an irregular mountain land with narrow valleys gives rise to a coast-line with deep and narrow inlets.

Another evidence of submergence is seen in the occurrence on many coasts of *submerged forests*. These are usually found on shelving coasts, where at low water the stumps of trees may often be seen with roots in the position of growth extending down into the deposits beneath. Examples are to be found at Swansea and elsewhere in the Bristol Channel, on the shores of the Mersey, and at many places in the English Channel.

While a coast of submergence shows the drowning of features due to agencies other than the sea, a coast of emer-

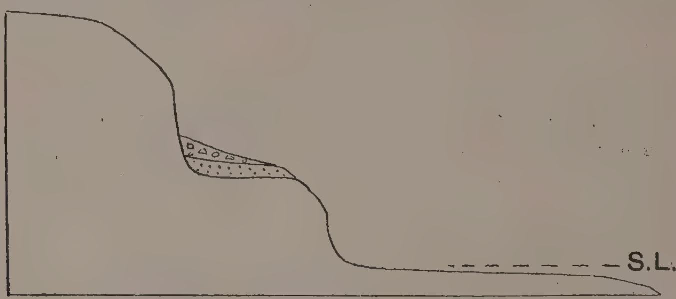


FIG. 48. Diagrammatic Section through a Raised Beach. S.L., sea level.

gence is marked by the occurrence at distances above sea level of features due to marine action. The most important of such features are *raised beaches* (Fig. 48). These are found at many points around the coast of Britain. A raised beach consists of beach material, sand or shingle often with sea shells, at a regular height above sea level; the beach may not be continuous all along a given coast, for at many places it will have been destroyed by the effects of wave erosion on the cliffs since its emergence. A raised beach will, however, be recognised in a number of localities, and it will be apparent from their heights above the sea that these are the remnants of a once continuous beach. Occa-

sionally the raised cliffs just behind the raised beaches show old sea caves, cut by the waves when the sea stood at this earlier level.

In some cases these emerged shores have no cover of beach material, either because it has been worn away or because no beach material was present: the emergence is shown however by the presence of *raised benches*, representing wave-cut platforms, which now stand at a level high above the platform which is being carved by the waves at the present time. Well-known raised beaches and benches in Britain occur at heights of about 25 feet and 50 feet above sea level.

A much greater uplift of the land is suggested by the occurrence of a very extensive wave-cut platform around

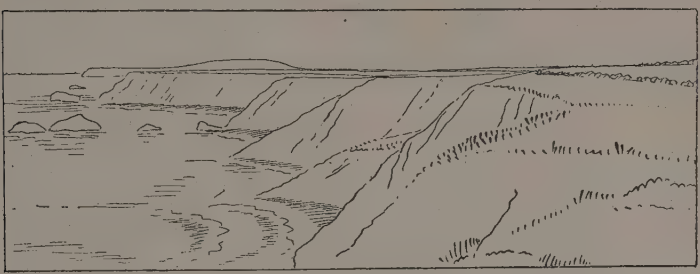


FIG. 49. The Coastal Plateau of North Cornwall (East of St. Ives). A wave-cut platform raised to form a smooth plateau.

many parts of the coasts of southern England and of Wales. It is especially well seen in Cornwall (*Fig.* 49), and in South Wales and Anglesey, where it has a width of many miles, and forms a gently sloping surface ranging from about 200 feet to 400 feet above sea level, and in some places ending abruptly inland against higher tracts where the ancient cliffs are sometimes recognisable. Into these coastal plateaux the rivers have cut their valleys, but the higher tracts rise to a uniform level and give rise to a remarkably even sky-line.

The Development of Coastal Forms. It will be apparent that many factors combine to determine the form of any particular coast-line. They include the erosive action

of the sea, the deposition of material by the waves, and the changes of sea level. The form depends moreover on the nature of the rocks forming the coast (which controls to a large extent the rate of marine erosion) and on the structural arrangement of rocks (which affects the form of the cliffs and determines the shapes and positions of many bays and headlands).

Changes in the relative levels of land and sea have had great influence on the pattern of many coasts, but it must be remembered that each such change brings a new strip of land within the reach of the erosive work of the waves, and thus leads to the inter-action of the other factors controlling the form of the coast. It may be noticed also that a coast-line produced by submergence owes much to the river erosion which occurred before the submergence, since the coast follows the pattern of the valleys, although here again subsequent erosion and deposition may lead to further modifications.

It may seem strange that parts of the British coast show evidences both of emergence and submergence; the submergence is a relatively recent occurrence (in some places it is believed to have continued since Roman times), which was preceded by movements of emergence at several different times. The submergence has drowned the lower parts of valleys which had been cut on land that had been upraised.

The Ocean Floor. The seas and oceans cover rather less than three-quarters of the earth's surface. Within this area there are great variations in depth, but there are several general features in the shape of the ocean floor which it will be useful to summarise here. Bordering the continents are relatively shallow waters, up to about a hundred fathoms in depth; in these areas the sea floor generally has gentle slopes, and although there are sometimes channels extending across it (perhaps representing former extensions of the river valleys of the land) the relief is much simpler than that on land. The North Sea and Irish Sea are shallow seas of this kind; westwards from Ireland the water remains similarly shallow for a distance of about 50 miles. Around

some continental margins, for example, along the west coast of America, the belt of shallow water is much narrower.

This area of shallow water is bounded by a region where the depth increases rather rapidly up to about 2,000 fathoms; then the ocean floor stretches as a broad and nearly level area for mile after mile, between the depths of 2,000 and 3,000 fathoms, broken here and there by gently rising ridges or by narrow deep depressions.

We may thus recognise four main units in the ocean floor: 1, the *continental shelf*, with a depth rarely exceeding 100 fathoms; 2, the *continental slope*, a narrow area where the depth increases rapidly; 3, the deep-sea plain or *abyssal plain*, with a depth of 2,000-3,000 fathoms; 4, a few small narrow "*deeps*," with depths sometimes exceeding 5,000

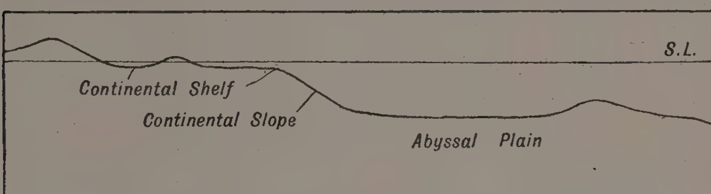


FIG. 50. Diagrammatic Section to show the general form of the ocean floor. Vertical scale much exaggerated.

fathoms. The continental shelf often seems to be a part of the continental area, and the real boundary between continent and ocean may well be taken at the position of the continental slope. These regions are shown diagrammatically, but with a much enlarged vertical scale, in *Fig.* 50. The following table shows the proportional areas of the different depths of the ocean floor:—

Between 0 and	1,000	fathoms	...	16 per cent.
,, 1,000 ,,	2,000	,,	...	19 ,, ,,
,, 2,000 ,,	3,000	,,	...	58 ,, ,,
,, 3,000 ,,	4,000	,,	...	7 ,, ,,
Over 4,000		,,	...	less than 1 per cent.

Deposits on the Ocean Floor. On the sea floor near the coast occur deposits of boulders and pebbles, sands and mud, which include some material carried into the sea by

rivers and some worn from the shores by waves. Very much of the debris derived from the erosion of the cliffs ultimately finds its way into the shallow water beyond the wave-cut platform. Much is carried by currents into deeper water. Such deposits of detrital material obtained from the land are found fringing all the continents, but they do not usually extend more than a few hundred miles beyond the shore. Besides these land-derived materials, of inorganic origin, material of organic origin also occurs. This consists of the remains of the skeletons of organisms, such as sea-shells, which may be mixed with the land-worn debris, or where such debris is lacking, may themselves give rise to deposits.

Into those parts of the ocean at a distance from continental margins very little land-derived material is carried; in those regions the ocean bed is covered by deposits formed in other ways. The nature of these deposits has been investigated by obtaining samples from the ocean floors at great numbers of localities; so much information has been obtained in this way as to the nature of the material on the ocean bed that maps showing the distribution of the various types of deposit have been prepared. The deposits in many places consist of the remains of small organisms which live in the sea. In particular great numbers of minute animals (including the *foraminifera* and *radiolaria*, p. 181) live in the surface waters of the ocean, and when they die their tiny skeletons (of calcium carbonate and silica) sink slowly to the bottom, forming deposits which cover many millions of square miles of the ocean bed. When samples of these deposits are brought up they are soft and loose; they are accordingly known as "*oozes*." Calcareous oozes are made up mainly of the remains of organisms whose skeletons consist of calcium carbonate, while siliceous oozes are similarly made up mostly of silica.

In some of the deeper parts of the ocean almost the only material deposited on the floor is a red clay, consisting largely of decomposed volcanic particles which may have been carried out over the ocean in the form of very fine dust: the rate of accumulation of such material is so slow that in

the Central Pacific the teeth of sharks which have been dredged from the bottom belong to species known to have been extinct for thousands of years, so that they must have lain unburied for all that time. These teeth consist of very resistant material, but the rest of the skeletons have disappeared, as also have the skeletons of the minute floating organisms which are common almost everywhere near the surface, but which dissolve in sinking down through miles of water.

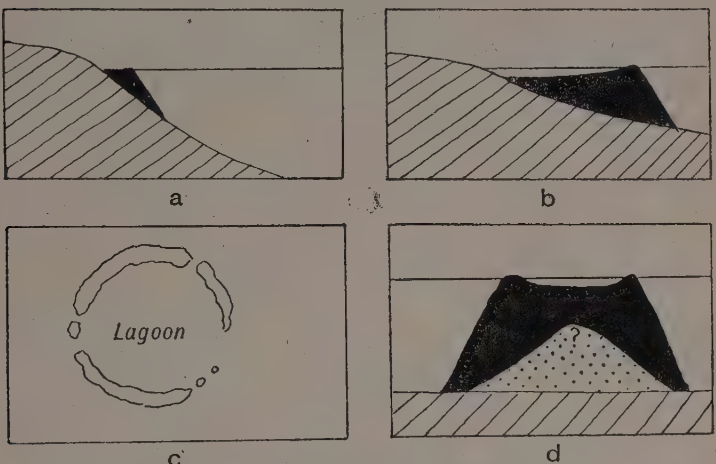


FIG. 51. Diagrams of Coral Reefs. a, Fringing reef; b, Barrier reef; c, Map of Atoll; d, Section of Atoll.

Coral Reefs. In the tropical seas there are many places where organically-formed material gives rise to reefs and to islands. In their formation corals have played a preeminent part. Those corals which are called reef-builders are colonial animals, each colony consisting of great numbers of simple and identical organisms which (like many marine organisms) have the power of extracting calcium carbonate from the sea water and of depositing it to form a skeleton. In the case of the corals the skeleton of a colony

may be like a bush with freely-dividing branches or it may be a dome-like mass. These skeletons are fixed during the lifetime of the colony (for only the newly-hatched larvæ of the corals are able to swim freely to other situations), but they may be broken away and moved by the waves, and deposited with the remains of sea weeds and other organisms to form massive rock.

Coral reefs are generally classed in three main groups. First there are *fringing reefs*, which are visibly attached to a land area; secondly, *barrier reefs*, extending more or less parallel to a coast line but at some distance from it, and leaving a broad channel between the reef and the land; lastly, there are *atolls* or coral islands of irregular shape, often circular, enclosing a central lagoon of comparatively shallow water which may be entered by one or more channels through the reef (*Fig.* 51). The Great Barrier Reef. the largest known example of a barrier reef, stretches for over a thousand miles along the north-eastern coast of Australia, at distances of 20 to 80 miles from it. Another barrier reef extends parallel to the north shore of Cuba.

Atolls are most frequent in the Pacific; they are the coral islands of some familiar stories. Often they rise quite abruptly from great ocean depths, and there has been much discussion as to their origin, for, although the upper part is composed of growing coral, it is not clear how the lower parts were formed since reef-forming corals cannot live in water much deeper than 20 fathoms.

It is not possible to discuss here the evidence in support of the various views concerning the origin of these reefs. It may be mentioned, however, that Charles Darwin, after his famous voyage in the "Beagle," first put forward an explanation of the relations of the different types of coral reef, suggesting that the fringing reef was always the first formed type, which became converted into a barrier reef and then an atoll as the sea floor sank. This elegant theory was widely accepted, but the very widespread subsidence of the sea floor which is required by this explanation raises many difficulties.

SUGGESTIONS FOR PRACTICAL WORK

Simple studies of wave motion (*e.g.*, in glass tanks, with corks to show surface movements).

Map studies of coastal forms.

QUESTIONS

1. Describe some of the processes by which the form of the land may be altered in the course of time. (C.W.B.Hr., 1934.)
2. Discuss the relative importance of erosion, deposition and change of sea level, in determining the forms of coast lines.
3. In what ways have (a) capes and headlands, and (b) bays and inlets, been formed? Mention some British examples and indicate their origin. (C.W.B.Hr., 1929.)
4. Describe the evidence as to movements of the land relative to sea level. (C.W.B.Hr., 1933.)
5. Draw a contoured sketch map of a country containing the following features:—corrie-lake, escarpment, waterfall, estuary, sea-cliffs. (C.W.B.Hr., 1933.)

CHAPTER VI

THE COMMON MINERALS

Quartz and Calcite. The study of minerals may usefully be begun by taking specimens of two such examples as quartz and calcite, and observing closely their similarities and differences. These are two of the commonest minerals, and both occur as "rock formers," quartz making up the bulk of sandstones and calcite of limestones. But in rocks the grains of minerals are small and mostly unsuitable for our present study, and it is better to collect specimens from veins or cavities in the rocks, especially from places where crystals have been able to develop. Both minerals frequently occur in hexagonal crystals; quartz forms hexagonal prisms ending in pyramids (*Fig.* 52), but although calcite forms somewhat similar prisms it occurs in a variety of other forms (*Fig.* 53). The faces of the quartz prisms are often marked by horizontal striations which make the distinction of the minerals very easy without any further test.

It is still easier to distinguish between them by testing the hardness of the specimens. If you take your pen-knife you will find that you can readily make a scratch on the calcite, but that you cannot mark the quartz; on the other hand the quartz will scratch the blade of your knife and will easily make a scratch on glass. It is apparent that quartz is a much harder mineral than calcite. This hardness is a dependable quality, for in this respect every piece of quartz behaves similarly.

Another useful test is to take a small piece of each mineral and break it up, using a little hammer and a small flat piece of steel as an anvil. The fragments should not be broken up too small at first, so that they can be examined

by the naked eye. It will be seen that the calcite breaks into quite regular pieces with smooth faces and parallel sides, each face being a parallelogram; these solid shapes are known as *rhombohedra* (singular, *rhombohedron*). If you break up one of the larger rhombs you will see that you get still smaller rhombs, and that the mineral continues to break along planes parallel to the outer faces. On the other hand quartz does not break up into regularly-shaped fragments; apart from the outside faces of the original crystal, all the broken faces are curved and irregular, while fresh fractures are not parallel to the existing faces. This difference in the manner of breaking is due to the fact that calcite is a mineral possessing good *cleavage;* the crystals

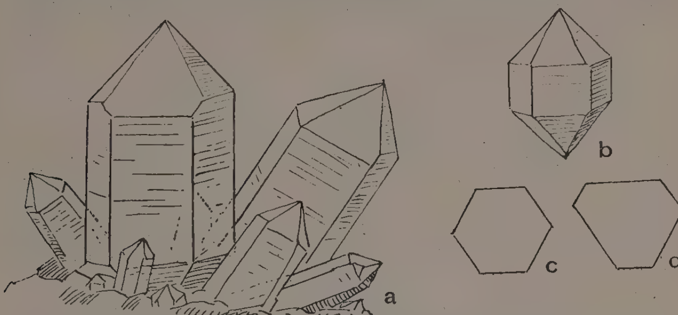


FIG. 52. Quartz. a, crystals; b, bi-pyramid; c, d, sections of crystals to show different developments of faces, with constant interfacial angles.

break freely along certain planes. In calcite there are three cleavage directions inclined to one another. Quartz does not possess any cleavage; there are no directions along which its crystals tend to break more freely than others.

Lastly, the test of chemical composition may be made to distinguish these minerals. Ultimately this is the absolute test, for every distinct mineral type has a definite chemical composition. In the case of the minerals we are examining, however, a very simple chemical test is sufficient to separate them. If a drop of dilute hydrochloric acid is placed on each, nothing is seen to happen in the case of

quartz, while calcite fizzes or effervesces rapidly. If a piece of calcite is dropped into a test-tube containing the dilute acid, the effervescence continues until all the calcite or all the acid has been used up. The gas evolved is carbon dioxide; the chemical composition of calcite is calcium carbonate, which is attacked by most acids. Quartz consists of silica or oxide of silicon, a very stable compound which is not affected by most acids; even hot concentrated hydrochloric acid has no chemical action on it.

Some of these characters by which minerals are determined must now be discussed in a little more detail: the sections which follow, however, should be studied in close connection with the examination of actual specimens. Only

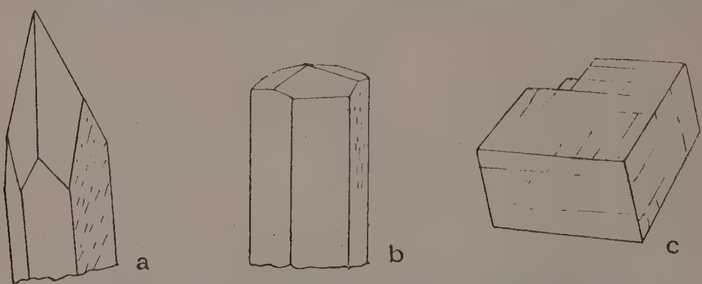


FIG. 53. Calcite. a, Dog-tooth spar; b, Nail-head spar; c, Rhombohedron showing 3 cleavage directions.

the outlines of the various topics are dealt with in each section, and the applications to the actual identification of minerals are left to later sections.

The Chemical Composition of Minerals. Some further attention may be given to the chemistry of the common minerals. Apart from graphite and diamond (which consist of the *element* carbon), sulphur, and a few metals which occur "native," all the minerals with which we are likely to be concerned are *compounds*, each containing two or more elements combined in definite proportions.

The composition of any one mineral is constant; for example, an analysis of calcium carbonate will always show the presence of 40 per cent. of calcium, 12 per cent. of car-

bon, 48 per cent. of oxygen. Except in the case of a few minerals, the composition remains constant throughout a single crystal; each portion of a specimen of quartz is built up in precisely the same way. This may be explained very simply as resulting from the fact that atoms of one element combine with atoms of another to form definite compounds; the number of atoms of one element always bears a simple and constant ratio to the number of atoms of the others with which it combines. Thus two atoms of oxygen combine with one of carbon to form a molecule of carbon dioxide; two atoms of oxygen with one of silicon to form a molecule of silica; four atoms of oxygen with three of iron to form a molecule of magnetic iron ore (magnetite). These facts about the composition of the minerals are embodied in the *formulæ* given below: the meaning of these will be better appreciated by readers with some knowledge of chemistry, however, and others will find it sufficient to remember only the composition in more general terms.

Certain elements are present in many minerals; oxygen is present in a great proportion of them, and silicon is also common. Indeed, if we consider the composition of the earth's crust as a whole, it appears that these two are by far the most abundant elements, for the average composition of the rocks of the crust is estimated to be approximately as follows:—

Oxygen	47 per cent.
Silicon	28 ,, ,,
Aluminium	8 ,, ,,
Iron	4·5 ,, ,,
Calcium	3·5 ,, ,,
Sodium, Potassium and Magnesium, each just over	2 ,, ,,

It is noteworthy that many of the metals—gold, silver, copper, lead, zinc and tin—together form less than ·5 per cent. of the earth's crust. As a rule they can only be worked in places where they have been concentrated by some natural process.

Hardness of Minerals. It has already been shown that quartz and calcite can readily be distinguished by the

difference in hardness. This character is of great value in the identification of many minerals, and is one of the first tests to be employed. This is usually done by scratching one mineral on another, or on some other substance of known hardness. A hard mineral will make a scratch on a softer: it is essential to make sure that a scratch has really been made, and not merely a streak of powder from a softer mineral.

In order to give some precision to this comparison of hardnesses it is useful to know the scale of minerals, known as Mohs' scale, arranged in order of hardness. This is as follows :—

1. Talc.	5. Apatite.	8. Topaz.
2. Rock Salt or Gypsum.	6. Felspar (Orthoclase).	9. Corundum (or sapphire).
3. Calcite.	7. Quartz.	10. Diamond.
4. Fluor Spar.		

It will be noticed that the last three in the list are gem-stones, in which hardness is an essential quality.

A mineral harder than quartz but softer than topaz may be said to have a hardness of 7·5, and so on. A pen-knife has a hardness of more than 6; it scratches felspar but is scratched by quartz (and topaz, etc.). The finger nail will scratch numbers 1 and 2, but will not (in most cases) scratch calcite. With a finger nail and a pen-knife therefore three groups of minerals can be separated.

In scratching a mineral a small quantity of powder is formed; in some minerals the powder is not the same colour as the mineral in mass. Thus iron pyrites, a brassy yellow mineral, has a black powder, while hæmatite, a grey or black mineral, has a red powder. The powder may also be studied by crushing a small fragment of the mineral or by rubbing a corner on a piece of unglazed porcelain, which gives a *streak*.

The Characters of Crystals. Practically all the minerals with which we are concerned are crystalline. This does not necessarily mean that every sample shows flat surfaces arranged in a definite plan, such as are to be observed in well-formed crystals. For crystalline structure depends

on the internal arrangement of the molecules or particles of matter, the shape of a crystal being an indication of the pattern of the internal structure. But many crystals have grown in cavities where they have merely filled up the available spaces; if they had been able to grow freely they would have formed regular and symmetrically arranged faces, but they have an irregular shape owing to the limitations of

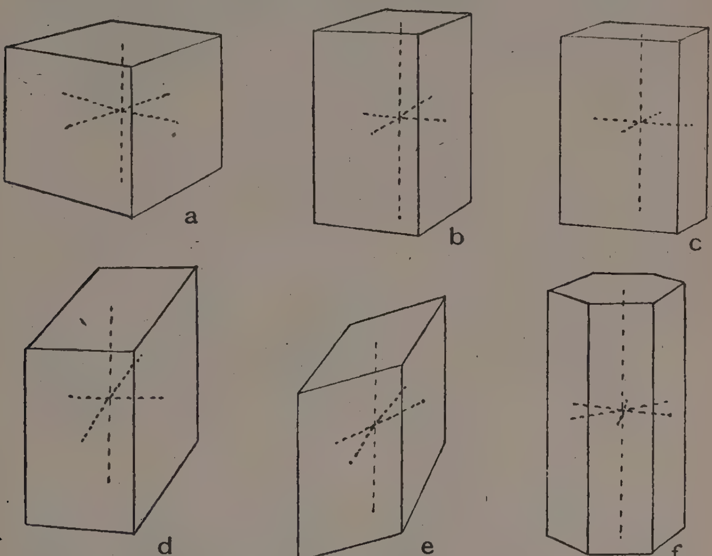


FIG. 54. Diagrams to illustrate the Crystal Systems; the crystallographic axes are shown by dotted lines. a, cubic system; b, tetragonal system; c, orthorhombic system; d, monoclinic system; e, triclinic system; f, hexagonal system.

their position. Many other mineral samples which show no obvious crystal shapes are made up of masses of very small (possibly microscopic) crystals, while others are fragments broken from large crystals.

There are, however, many common specimens which show the crystal form more or less completely, and it is necessary to know something of the plans on which crystals

are built. A perfect crystal is bounded by *faces* which are usually flat (although they are sometimes curved, as in dolomite, the carbonate of magnesium and calcium). When all the faces in a crystal are identical in character it is called a *simple form* (*e.g.* a cube or an octahedron, *Figs.* 54a, 61); a crystal containing faces of more than one type is said to be a *combination* of forms (*e.g.* the crystal of quartz, showing the hexagonal prism capped by a pyramid, *Fig.* 52).

The angle between adjoining faces of a crystal

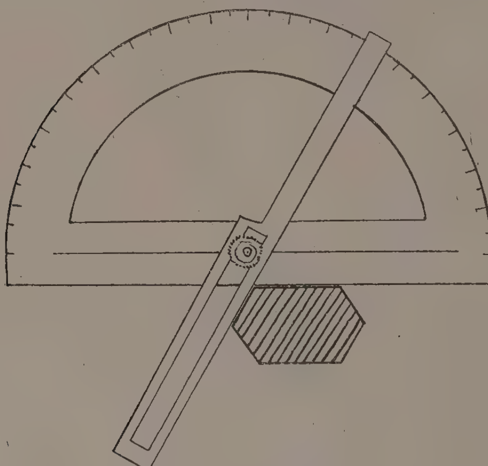


FIG. 55. A simple type of contact goniometer.

(known as the *interfacial angle*) is constant for any particular mineral; thus the interfacial angles in a cube are 90 degrees, those of the prism in quartz are 120 degrees. The interfacial angles remain constant even when there is marked variation in the relative sizes of the faces: a crystal of quartz may not be a regular hexagon in section but its interfacial angles do not vary (*Fig.* 52c, d). The measurement of interfacial angles may in some cases afford very useful information as to the identification of the mineral, and it is often useful to measure them. For this purpose an instrument known as a *goniometer* is used: a simple type of contact goniometer

is shown in *Fig.* 55. Such an instrument may be used to test the constancy of interfacial angles in different specimens of any given mineral.

Crystals are of many different shapes, but all the various types have been classified into six *crystal systems*. Calcite and quartz belong to the Hexagonal System, which includes crystals with hexagonal prisms and pyramids in various combinations. The Cubic System includes not only cubes but also octahedra (regular 8-faced solids), dodecahedra (12-faced solids) and other forms. The placing of these different forms within one system may be better understood if it is pointed out that all of these can be regarded as built up around three axes which are equal and at right angles to one another; such axes are shown by dotted lines in *Fig.* 54. They are known as the *crystallographic axes*.

In the next system, the Tetragonal, all the crystallographic axes are again at right angles, but only two of them are equal in length; Tetragonal crystals thus include square prisms. The Orthorhombic System has three axes at right angles, all of them unequal; it includes oblong prisms. The Monoclinic System has three axes, all unequal, only two at right angles to one another, the third inclined. The Triclinic System has three axes, all unequal and none at right angles.

It will be readily apparent that the cubic system contains the most regular or symmetrical crystal shapes; a cube can be turned through 90 degrees about any axis without making any real difference to the space it occupies, a hexagonal or square prism can only be rotated in one plane if it is to occupy the same space, while a triclinic crystal cannot be turned in any direction without altering its space relations. The minerals of simplest composition generally have the more regular shapes, while many of the more complicated minerals occur in the monoclinic or triclinic systems. This is due to the difference in the complexity of the molecules which build up the crystals.

Density and Specific Gravity. In separating many minerals the difference of density or specific gravity is of extreme value. The *density* of a mineral may be defined as

the weight of a unit volume; the *specific gravity* of a mineral is the ratio of the weight of a sample to the weight of an equal volume of water. Thus the density of galena is about 7·5 grams per cubic centimetre; since 1 c.c. of water weighs 1 gram, the S.G. (specific gravity) of galena is also 7·5.

The density of many minerals may easily be found by weighing carefully a specimen and then placing it in a measuring cylinder containing water; if the reading of the water level is taken before and after putting in the specimen the difference will give the volume of the specimen (provided that it is quite solid and that no air bubbles are allowed to remain attached to it). Other methods of determining density or specific gravity need not be discussed here. It may, however, be useful to state that a rapid separation of fine grains of different minerals can often be made by using a liquid which has a high specific gravity. A liquid commonly used for this purpose is bromoform, which has a specific gravity of 2·9. In this, such minerals as quartz and calcite float, but minerals such as galena and most other ores sink to the bottom. The heavy minerals in a rock can thus be readily separated out if a crushed sample is placed in bromoform.

Quartz and other forms of Silica. The general characters of quartz have already been stated. The more important may be summarised :—

Composition: Silica, oxide of silicon (SiO_2).

Crystal System : Hexagonal; prisms often terminated by hexagonal pyramids.

Hardness: 7. S.G.: 2·65.

No cleavage; Quartz breaks with a curved fracture, with markings which sometimes resemble the concentric lines on a shell. This type of fracture is called *conchoidal* (meaning shell-like).

Quartz is ordinarily colourless; *rock-crystal* is a clear, transparent form of quartz. Frequently quartz is clouded because small grains or crystals of other minerals are included. Some varieties have distinct colours due to certain impurities; *Amethyst* (sometimes used in jewellery) is a violet variety; *rose quartz* is pink, *smoky quartz* is brown,

and *milky quartz* is white. This variety of colours found in a single mineral, resulting from the presence of very small amounts of other material, illustrates how colour may be an uncertain guide in identifying many minerals, whereas other simple tests are reliable since the main properties of the crystals are constant in all the different varieties.

Silica also occurs in nature in several other forms. The most important of these consist of masses of crystals so minute that they can scarcely be recognised as crystals even under a microscope. *Chalcedony* usually occurs in cavities, and may be pale grey or brownish in colour.

Agate is a form of chalcedony consisting of alternating layers of different colour, representing successive deposits in a cavity (*Fig.* 56). When cut and polished agate makes

FIG. 56. Agate, seen in section.

a very decorative stone. *Jasper* is a red and opaque variety of silica. All these minerals are hard and cannot be scratched by a knife.

Flint, which may be regarded as a rock and not a mineral, consists of a compact form of silica in which the crystals are similarly very minute; flint is very familiar in Chalk areas, for it is found in nodules which occur in layers within the Chalk: pebbles of flint derived from the denudation of Chalk areas also occur commonly in many gravels and on many beaches. Flint varies in colour from grey or brown to black. It breaks with a very distinct conchoidal fracture, and because of its hardness it was much used by prehistoric man for the making of weapons and tools; as it gives a spark when struck by steel, it was also long used for gun-flints. *Chert* is a similar material, mostly occurring

in nodules in limestones, and it breaks with a less regular fracture.

Opal is another form of silica, rather softer than quartz, generally pale in colour but showing a play of colours (yellow, red and brown) as the mineral is turned in the light. Opal is not crystalline but *amorphous:* it is one of the few amorphous minerals.

Calcite. The more important characters may be summarised :—

Composition: Calcium carbonate ($CaCO_3$).

Crystal System: Hexagonal; commonly hexagonal prisms, terminated by three nearly flat faces (nail-head spar) or by steeply inclined pyramid faces (dog-tooth spar).

Hardness: 3. S.G.: 2·7.

Cleavage: Three perfect cleavages along which calcite breaks into rhombohedra.

Calcite is mostly colourless or white, but is often coloured by the presence of small quantities of other minerals; a red staining due to iron compounds is frequent. Very pure calcite (*Iceland spar*) is quite transparent. Printing viewed through a slab of Iceland spar is seen twice, owing to the fact that each ray of light entering the spar is split into two distinct rays which emerge separately and convey separate images to the eyes.

Calcite is extremely common in limestone areas, where it not only occurs in veins but makes up (in the form of minute crystals) much of the limestone itself and also the tufa and stalactites and stalagmites characteristic of those areas.

Dolomite (Pearl Spar). Dolomite is another carbonate, with many points of resemblance to calcite. In composition it is carbonate of magnesium and calcium ($CaCO_3.MgCO_3$).

Crystal system: Hexagonal, commonly occurring in rhombohedra, often with curved faces.

Cleavage: as in calcite.

Hardness: 3·5-4. S.G. about 2·8.

Dolomite is often pale brown or yellow in colour, with a pearly lustre. It occurs with galena in some ore veins

and also as the main constituent of dolomitic limestone (*magnesian limestone*).

Rock Salt. This mineral usually occurs *massive,* small crystals packed together making up beds some feet in thickness, and it is in this form that most salt is mined, as in Cheshire. Occurring frequently amongst red rocks, rock salt is commonly red or yellow; when pure, however, it is colourless or white.

Composition: Sodium chloride (NaCl).

Crystal system: Cubic. It crystallises in cubes with hollow faces.

Cleavage: Parallel to the cube faces.

Hardness: 2. S.G. 2·2.

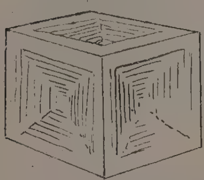


FIG. 57. A cube of salt, showing hollow faces.

It need not be said that this mineral can be recognised by its taste. Some samples of rock salt which contain impurities are *hygroscopic,* attracting moisture from the atmosphere. Consequently they are not easily kept in a collection except in corked tubes.

While rock salt only occurs commonly at a few places in Britain, hollow cubes made of mud, having the form of salt crystals, are much more widespread, being found in many places in the Midlands. They represent salt crystals, formed during the evaporation of the waters of a salt lake, which were re-dissolved by an inrush of fresh water; the hollows left were then filled with mud which thus reproduces the form of the crystals. These mud cubes are known as "*salt pseudomorphs*"; a pseudomorph is a solid which assumes a crystal form characteristic of some other substance.

Fluor Spar. Composition: Calcium fluoride (CaF_2).

Crystal system: Cubic, occurs in cubes often with octahedral faces.

Cleavage: Parallel to octahedral faces. If a perfect cube of fluor spar is tapped lightly at a corner, a piece will break away inclined equally to all the cube faces, leaving a new and triangular face. If

this is done at every corner, 8 new faces will have been produced: these are octahedral faces, for if sufficiently big pieces are cut from the crystal along these planes the cube faces will disappear and the final form will be an octahedron. This feature is illustrated in *Fig.* 58; it is explained in some detail here because it serves to emphasise the relation of cubes and octahedra as forms within the cubic system.

Hardness: 4. S.G.: About 3·0.

Fluor spar varies in colour. It is usually clear and glassy, but it may be colourless, yellow, green, blue or purple: sometimes two of these colours are combined very attractively in a single crystal. *Blue John* is a deep blue variety found in Derbyshire. Fluor spar often occurs in veins with galena and tin ores.

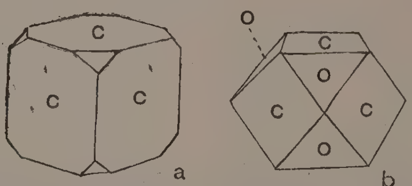


FIG. 58. Crystals of Fluor Spar; a, with corners of cube truncated along octahedral cleavages; b, with a further degree of truncation, the crystal showing cube (c) and octahedron (o) faces.

Gypsum. Composition: Hydrated calcium sulphate (that is, calcium sulphate chemically combined with a fixed proportion of water, $CaSO_4.2H_2O$).

Crystal system: Monoclinic.

Cleavage: One perfect cleavage. A thin flake can be bent without breaking.

Hardness: 2 (can be scratched with the finger nail). S.G.: 2·3.

Gypsum commonly occurs massive in the Midlands, in more or less continuous beds several feet thick. It is normally white but may be stained pink, for it often occurs among red rocks rich in iron oxides. *Alabaster* is a compact massive variety used as a decorative stone and for statuary, especially in churches; it is too soluble for outdoor use.

Massive gypsum is also mined for the manufacture of plaster of Paris, formed by heating to drive off some of the combined water.

In large crystals, gypsum is known as *selenite*. These are shaped as shown in *Fig*. 59a, where the direction of the cleavage is also indicated. *Twin crystals* occur in which two crystals are evenly united: it appears as if a single crystal had been cut in two and one half rotated through 180 degrees before being re-attached (*Fig*. 59b). Twins are found in other minerals, but the simple twinning of selenite forms an easy illustration of the character.

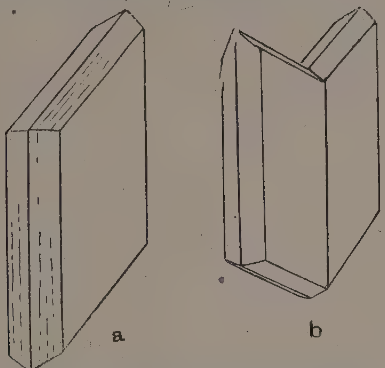


FIG. 59. Selenite (Gypsum) crystals. a, simple monoclinic crystal; b, "butterfly twin."

Another form of gypsum is *satin spar*, which is a fibrous variety, with a silky appearance. In this the crystals are long and needle-like, and the satin spar generally represents a vein filling a crevice in which crystals grew inwards from the two walls, meeting somewhere near the centre.

THE METALLIC MINERALS

The minerals next dealt with are metallic minerals. Most of them have a metallic lustre and all have a high specific gravity.

Galena. Galena has long been one of the chief sources of lead, and its leaden colour makes its relation to the metal easy to remember.

Composition : Lead sulphide (PbS).

Crystal System : Cubic; often in cubes, sometimes with octahedral faces.

Cleavage : Parallel to cube faces; crystals will easily break into cubes.

Hardness : 2·5. S.G. : About 7·5.

Galena, heated on a piece of charcoal in a blowpipe flame, yields a shining globule of metallic lead. It is one of the easiest metals to obtain from its ore.

Galena mostly contains some silver (also present as a sulphide). It occurs in veins in a wide variety of rocks.

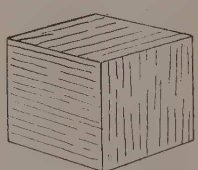


FIG. 60. Iron Pyrites. Cube showing striated faces.

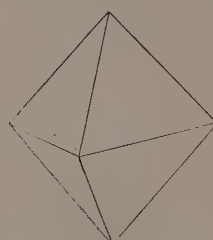


FIG. 61. Magnetite Crystal.

Zinc Blende. Composition : Zinc sulphide (ZnS).

Crystal system : Cubic : tetrahedra (4-faced solids) and dodecahedra occur, but the crystals are often much twinned and intergrown, and the form is not usually easy to determine.

Cleavage : Good; blende broken across its cleavage directions shows a conchoidal fracture.

Hardness : About 3·5. S.G. : About 4·0.

There is rarely any difficulty in distinguishing blende owing to its bright lustre. It varies in colour but is mostly dark brown, though sometimes yellow. Usually it is transparent or translucent in thin pieces.

Iron Pyrites. Composition: Iron sulphide (FeS_2).

Crystal system: Cubic, commonly occurs in cubes with striated faces (*Fig.* 60); also in dodecahedra with pentagonal faces. It also occurs massive.

Cleavage: None. It breaks with an irregular conchoidal fracture.

Hardness: Just over 6 (not scratched by a knife). S.G.: About 5.

Iron pyrites is brassy yellow or gold in colour, with a metallic lustre. (It is often called "Fool's Gold"). The streak is brownish black. It occurs very widely in many types of rock, and in veins and nodules. The brassy mineral often present in coal is iron pyrites. It is not used as a

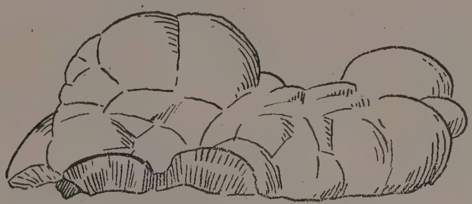


FIG. 62. Kidney Iron Ore (Hæmatite).

source of iron. On the other hand, *copper pyrites* is an important source of copper; this usually has a more vivid colour and is readily distinguished as its hardness is under 4.

Magnetite. Composition: Oxide of iron (Fe_3O_4).

Crystal system: Cubic, commonly in octahedra (*Fig.* 61).

Cleavage: Poor.

Hardness: About 6. S.G.: About 5.

Magnetite is readily distinguished as the magnetic ore of iron; grains are attracted by an ordinary magnet. It occurs in many parts of the world in small quantities, and is an important ore of iron in north Europe and Siberia.

Hæmatite. Composition: Oxide of iron (Fe_2O_3).

Crystal system: Hexagonal; crystal form rarely well shown except in the variety known as *specular iron ore,* which has rhombohedral crystals.

Cleavage: Poor.

Hardness: About 6. S.G.: About 5.

Hæmatite mostly occurs massive, often shows a fibrous structure on its fractured surfaces. In colour it is normally black or grey, but it has a red streak, and when a specimen has been broken the powder gives a red colour. *Kidney iron ore* is a variety with a *mammillated* surface, that is, one made up of intersecting spheroidal surfaces (*Fig.* 62).

Limonite is another ore of iron, also an oxide, but differing in the presence of combined water ($2Fe_2O_3.3H_2O$): thus the percentage of iron in limonite is less than hæmatite. Limonite gives a brownish streak and is thus easily distinguished.

Red and brown ochres are earthy forms of these oxides which are used in the manufacture of paint.

Hæmatite is commonly found in veins and masses in limestone areas, as in Cumberland, at Ulverston (Lancs.) and the Forest of Dean.

The Silicates

The minerals dealt with hitherto are mostly of simple chemical composition: those to be dealt with here are more complex. All of them may be regarded as containing the oxide of silicon in combination with oxides of various metals. These compounds are silicates: it must be realised that the oxide of silicon (or silica) in quartz is free and uncombined, and that nothing else is present in the quartz. The silica of the silicates is not quartz, for it is chemically combined with other oxides to form distinct compounds. Silicates are of great importance since they make up the bulk of the igneous rocks; those dealt with below are the most abundant.

Felspars (or Feldspars). We have already learned that granite consists of quartz, felspar and mica; there are, however, many kinds of felspar, each with a distinctive chemical composition. For our purpose it will be sufficient to distinguish *orthoclase* and *plagioclase* felspars.

a. Orthoclase felspar.

Composition: Potassium aluminium silicate ($K_2O.Al_2O_3.6SiO_2$).

Crystal system: Monoclinic. Commonly occurs in prismatic crystals; sometimes twinned (*Fig.* 63).

Cleavage: Two perfect cleavages which are at right angles (hence the name, which means "splitting straight").

Hardness: 6. S.G.: 2·57.

Orthoclase is mostly pink or white in colour, transparent in thin sections. It is abundant in granite.

b. Plagioclase felspars.

Chemical composition: They may be summed up as sodium, calcium, aluminium silicates, the proportion of sodium to calcium varying in different

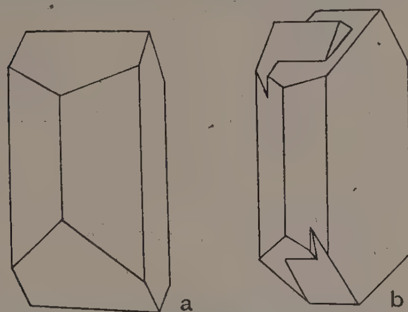


FIG. 63. Orthoclase Felspar; a, monoclinic crystal; b, Carlsbad Twin.

varieties. With these differences in composition, changes in physical characters are found.

Crystal system: Triclinic; prismatic crystals most common. Plagioclase felspars usually show *repeated* or *lamellar* twinning, each specimen consisting of a large number of twinned crystals arranged regularly side by side as thin plates (not merely of two as in *Fig.* 63b). This character often gives rise to the appearance of a fine parallel ruling on specimens, which can be seen by the naked eye.

Cleavage: Two cleavages which are not quite at right angles.

Hardness: 6-6·5. S.G.: 2·62-2·77.

Plagioclase felspars vary in colour from whitish to grey. One variety, *labradorite*, often shows a play of colours by reflected light (mostly blue and green). It is seen in polished slabs of some igneous rocks used in decoration.

Plagioclases are abundant in many igneous rocks.

By exposure to weathering, especially in the presence of moisture, or by the action of hot gases, felspars are altered, the alteration resulting partly from the combination of water with the substances present: this process is called

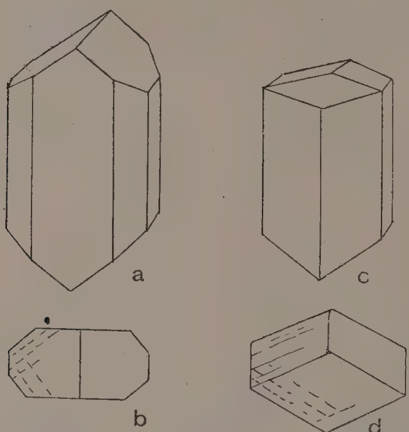


FIG. 64. a, b, Augite; c, d, Hornblende. b and d show the crystals in plan; with the cleavage directions added.

hydration. The products are mostly *micas*, but from orthoclase *kaolin* (China clay) has been formed in this way; it is a white soft clayey material consisting of hydrated silicate of aluminium ($Al_2O_3.2SiO_2.2H_2O$).

Mica. Mica is also a mineral commonly found in granite and other igneous rocks. Mica occurs as an original constituent of these rocks and also as an *alteration product* of felspars; mica is also present in many sedimentary rocks. Large crystals of mica are sometimes

found in veins associated with igneous rocks. Two types of mica may be mentioned, *muscovite,* or white mica, and *biotite,* or black mica. Both are monoclinic and are characterised by occurring in six-sided plates with one set of perfect cleavages along which the mineral may be split into sheets of extreme thinness, which are elastic: they can be bent and will spring back to their original positions.

a. Muscovite, or white mica.

Composition: Potassium aluminium silicate, with water, $(K_2O.3Al_2O_3.6SiO_2.2H_2O)$.

Hardness: 2-2·5. S.G.: 2·8.

b. Biotite.

Composition: Variable; a silicate of magnesium, aluminium, potassium and iron together with water.

Hardness: 2·5-3·0. S.G.: About 3·0.

Hornblende. Composition: Variable; a silicate of calcium, magnesium and iron often with other constituents.

Crystal system: Monoclinic; occurs in six-sided prisms which have the shape shown in section *Fig.* 64d. The termination of the prisms usually consists of 3 gently inclined faces (*Fig.* 64c, d).

Cleavage: Two cleavages at an angle of nearly 120 degrees.

Hardness: 5-6. S.G.: Just over 3·0.

Hornblende is black or dark brownish green in colour, transparent in thin sections, almost opaque in normal specimens. It occurs in many igneous and metamorphic rocks.

Augite. Composition: Variable; a silicate of calcium, magnesium, iron and aluminium.

Crystal system: Monoclinic, often in eight-sided prisms (see *Fig.* 64a, b) terminated by two roof-like faces (compare hornblende).

Cleavage: Two cleavages nearly at right angles (compare hornblende).

Hardness: 5-6. S.G.: Just over 3·0.

Augite is black or greenish black. In appearance it is much like hornblende, and care is often necessary to separate these minerals. It occurs in many igneous rocks.

Olivine. Composition: Iron and magnesium silicate, $2(Mg,Fe)O.SiO_2$.

Crystal system: Orthorhombic; sometimes in prisms, more frequently in irregular masses.

Cleavage: None.

Hardness: 6-7. S.G.: 3-4.

Olivine is mostly pale green in colour. It occurs in igneous rocks (commonly in basalt). Olivine in contact with water becomes hydrated to form the mineral *serpentine,* which is usually green. It sometimes completely replaces the olivine in a rock, and therefore forms a pseudomorph. Serpentine is also formed by the alteration of augite and hornblende.

SUGGESTIONS FOR PRACTICAL WORK

The study of actual specimens must form an important part of the practical work. Besides a reference collection of good samples, pupils should freely handle specimens of less value; these samples should be available for breaking up, scratching and other tests. It is useful to have such specimens unlabelled (two or three different minerals at a time) and to determine them from given data.

Determinations of specific gravity by various methods (according to the knowledge of hydrostatics possessed by the student). Use of a contact goniometer.

Simple chemical tests as mentioned in the Chapter, such as the action of acid on carbonates and the preparation of at least one metal from its ore, should be undertaken by those who have little previous knowledge of chemistry.

The making of some simple crystal models from thin cardboard or from plasticine.

QUESTIONS

1. What tests would you apply in trying to identify a series of unknown minerals? (C.W.B.Hr., 1935.)
2. Draw up lists of minerals (a) which can be scratched by the finger-nail; (b) which can be scratched by a knife and (c) which are harder than steel.
3. Give the composition and distinctive characters of fluor spar, calcite, hæmatite, galena, white mica. Which of these substances are of economic importance, and why? (C.W.B., 1934.)
4. Explain carefully, with diagrams where necessary, how you would distinguish between hæmatite and limonite; quartz and calcite; augite and hornblende; magnetite and galena.

CHAPTER VII

THE SEDIMENTARY ROCKS

Some of the ways in which debris is transported and new sediments formed have been discussed in the previous chapters. The production of coarse angular talus material, the weathering and sorting and breaking up of fragments of various types by water action (both by rivers and the sea), the deposition of material on land, in lakes and in the sea, are all factors to be considered in the origin of the different kinds of sedimentary rocks. The formation of sedimentary rocks from the skeletons of various organisms has also been mentioned. In this chapter the rocks themselves are dealt with, and attention is directed to those more obvious characters in the rocks which serve to distinguish them or which throw some light on their modes of origin.

The sedimentary rocks may be classified in several ways. It is possible to group them according to their mode of origin into :—

(1) Mechanical Deposits—resulting directly from the accumulation of debris formed by the destruction of pre-existing rocks; these include sandstones, muds, boulder clay, etc.

(2) Chemical Deposits, formed as precipitates from solution by evaporation or under various other conditions; these include calcareous tufa, salt deposits, etc.

(3) Organic Accumulations, formed by living organisms; these include many types of limestone, coal, etc.

It will be more convenient, however, to group them according to the nature of their chief constituents, into :—

(1) The Arenaceous or sand rocks, (2) the Argillaceous or clay rocks, (3) the Calcareous rocks (or limestones), (4) the Siliceous rocks, (5) the Carbonaceous rocks.

Arenaceous Rocks. The typical rocks of this class consist mainly of sands and sandstones, but it will be convenient to include here also those rocks (sometimes called the *Rudaceous* rocks) which consist of coarser material than is ordinarily to be found in sandstones.

An ordinary sandstone is largely made up of grains of quartz, usually of fairly constant size in any particular

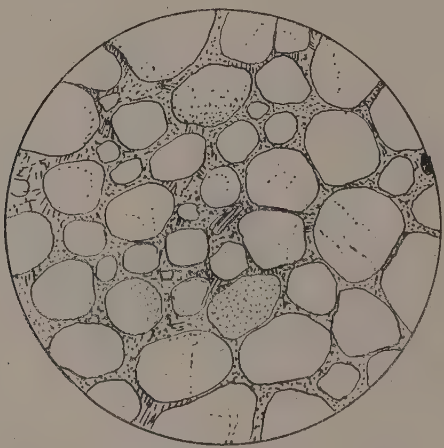


FIG. 65. Sandstone (Greensand, Berkshire). Seen in a thin slice under the microscope, showing rounded quartz grains cemented together. Magnified 15 diameters.

sample, and often smooth and rounded. These grains are held together by a cementing material, and the toughness of the sandstone depends most of all on the nature of the cement. One of the most frequent cementing materials is calcium carbonate: this has been introduced between the grains by underground waters possibly long after the forma-

tion of the original deposits of sand grains. When such a sandstone is broken, the fracture follows the calcareous cement, and the quartz grains, being harder, are rarely broken across; the surface is thus slightly irregular and the projecting grains can be detected. If such a sandstone is scratched by a knife, a grating sound is caused, and a mark is left on the surface, although, of course, the quartz grains themselves are not broken or scratched. Similar features are shown in sandstones which have a cement of clayey material.

Sandstones may be of various colours; red sandstones mostly owe their colour to the presence of red iron oxide, which may occur as a thin film surrounding each grain. Other compounds of iron give a greenish or grey colour; these compounds may by oxidation give rise to the red and brown oxide and thus the outer portion of a sandstone may be of different colour from the inner. Some sandstones split into thin beds very easily: they are said to be *fissile*. Thin-bedded sandstones are used as *flagstones*.

The diameter of the grains in a sandstone may average about 1 mm. or less than 0·1 mm. When the grains are less than this the rock is sometimes called a *siltstone*, for the grains represent a *silt* rather than a sand. The evenness of the grain size in any particular sandstone is mostly due to the sorting action of the water by which it was deposited. It is useful to break up a number of different sandstones into their constituent grains to examine their grain sizes. Various ways of separating the grains according to their size may be used; the use of sieves is one of the most convenient.

Sandstones nearly always contain grains of other minerals besides quartz, but often these form a very small proportion of the whole. Mica is frequently present, sometimes in such quantity that the rock is called a *micaceous* sandstone; the flakes of mica are usually arranged with their faces parallel to the bedding of the rock, and they tend to make it split into thin even slabs. Felspar is less abundant in sandstones, for the reason that it is rather un-

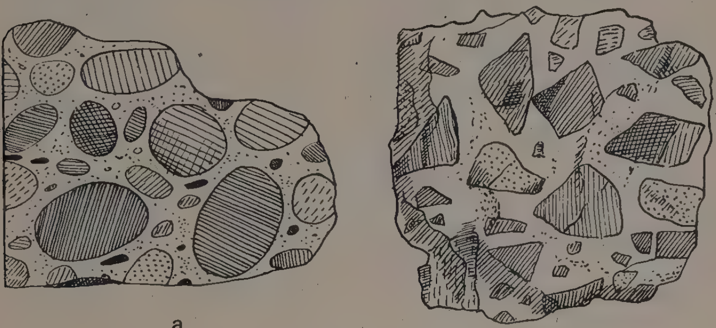
stable under conditions of ordinary weathering. When an igneous rock becomes disintegrated the felspars are usually altered, giving rise to micaceous and clay minerals which contribute largely to the formation of argillaceous rocks. For this reason felspars do not ordinarily travel unchanged for very great distances from their original home in an igneous rock, but sandstones derived directly from a neighbouring granite mass may contain abundant felspars. Such a sandstone is known as a *felspathic* sandstone or an *arkose*. In this connection it must be remembered that quartz grains in any sandstone, although probably derived from an igneous rock in the first place, may subsequently have formed part of another sandstone and may have been derived from it to form the rock in which they are now found: quartz is a very stable mineral which is not easily altered, hence its persistence.

Another type of arenaceous rock which contains abundant material besides quartz is known as a *greywacké* (or graywacke). This is generally dark and is mostly of a grey colour. It is composed of rounded or angular grains of quartz, felspar (chiefly plagioclase) and other minerals; many greywackés also contain small angular fragments or flakes of other rocks such as slate. Frequently the grains are of varied sizes. The term is commonly used for some of the old rocks of the Southern Uplands of Scotland and of Wales.

Quartzite is a form of sandstone resulting from the cementing of the sand grains by silica; such a rock may thus consist almost wholly of silica. It is very tough, and cannot be scratched by a knife. When a quartzite is broken the fracture does not pass any more easily through the cement than through the grains, since both are quartz. The broken surface shows none of the peculiarities of an ordinary sandstone, grains are not easily separated, and the fracture has a peculiar greasy appearance.

The term *grit* (or *gritstone*) is variously used by different geologists. Some regard grit as a coarse sandstone, others apply the term to a sandstone with angular (not rounded) grains; if the term is used it is desirable to state in which sense it is employed.

The coarser rocks of this class include gravels and pebble beds. A *conglomerate* is a pebble-rock or boulder-rock in which the fragments ("grains") are of very large size, up to some feet in diameter (*Fig.* 66a). The pebbles and boulders are rounded, showing that they have been carried for some distance from their source and that they have been battered either in a torrent or by waves. The material of the pebbles may be of any kind of rock, igneous or sedimentary; the variety of conglomerate is usually named from the nature of the pebbles, so that granite conglomerate, flint conglomerate, quartz conglomerate, limestone con-



a b

FIG. 66. a, Conglomerate; b, Breccia.

glomerate, etc., may be recognised. The matrix is generally coarse, sandy material. All conglomerates have been formed in shallow water, powerful currents being essential for the transport of the heavy material.

A *breccia* is in many ways like a conglomerate, consisting of fragments of rock set in a matrix of somewhat similar material; in the case of a breccia, however, the fragments are not rounded but angular (*Fig.* 66b). The material has thus undergone little or no transport, and often represents scree or talus material which has been carried only a short distance from its source. Most breccias have been formed as sub-aerial deposits, but others have been laid down in shallow water.

Argillaceous Rocks. Clay is a typical argillaceous rock. The grains resulting from the crushing of a piece of clay are of very small size; few exceed ·01 mm. diameter. These fine grains represent the material which has been transported (usually by water) further than the coarser material could be carried: they represent the finest particles produced by rock weathering. The actual minerals present are not easily identified as the grains are so extremely small, but they include micaceous and kaolin-like minerals. Other constituents found in smaller quantity in many clays include quartz grains (an increase in the amount of quartz giving a sandy or gritty clay, which only differs to a slight extent from a clayey sandstone), calcareous matter and finely divided iron pyrites. Many, but not all, clays are plastic.

A *shale* is a clay rock which splits easily along its bedding planes into thin layers: in a *paper shale* these layers are extremely regular and the layers in a band of paper shale a few inches thick can often be turned like the pages of a book. A *mudstone* is a more compacted form of clay which ordinarily lacks plasticity, and does not possess the fissility of shale. A *slate* is an argillaceous rock which has been affected by intense pressure; the characters of slate are discussed below (Chap. X).

A *bituminous shale* is one which is rich in organic matter and on distillation yields oil. Bituminous shales at Kilve in Somerset will burn irregularly with a smoky flame; the oil-shales of the Scottish lowlands yield considerable quantities of oil.

A *fireclay* is one which can be subjected to high temperatures without melting: this quality results from the absence or scarcity of those substances (such as the alkalis, soda and potash) which promote melting. They are used for making bricks for furnace linings. Many of the fireclays worked in England occur beneath coal seams, where they appear to represent "fossil soils" in which the trees forming the coal grew. Extending down into many fireclays are roots and rootlets of these trees, which frequently interrupt the original bedding so that the fireclays break irregularly.

The term *marl* is used rather loosely, but typically a marl is a calcareous clay which usually shows only indistinct bedding planes and weathers into small cubical or dice-like pieces. By an increase in the amount of calcareous matter a marl passes into an earthy (or argillaceous) limestone, and here again there is no definite line of demarcation between the two classes: obviously, if a marl and a limestone are being formed simultaneously on different parts of the sea floor it may be expected that they will merge into one another in the intervening area. The different types of sedimentary rock are not always sharply marked off from one another.

Calcareous Rocks. Limestones vary greatly in appearance: they may be white, grey, red, yellow or black in colour, according to the amount and nature of iron compounds or other non-calcareous matter that is present; they may be smooth-fractured and almost uniform in structure to the naked eye, or they may be ragged on broken surfaces and show much detail of structure; they may be compact or very porous. All limestones, however, consist largely of calcium carbonate, the presence of which is soon shown if the rock is treated with cold dilute hydrochloric acid. At one time many geologists carried small acid bottles into the field to test limestones; this is not often necessary, as a limestone can usually be recognised in other ways, but it is useful practice for the beginner to apply acid to rocks thought to be limestones (to the corners or edges in order not to deface the specimens). It is also useful to allow fragments of limestones to dissolve completely in dilute acid, to estimate the proportions of the residues and to examine their characters with a lens. Many limestones have less than 5 per cent. of insoluble matter: some argillaceous limestones have over 30 per cent.

Since limestones consist mainly of calcite they may easily be scratched with a knife, and in scratching them there is no grating sound such as is made in scratching a sandstone.

In many types of limestone there are evidences of organic remains, such as the skeletons of corals and various

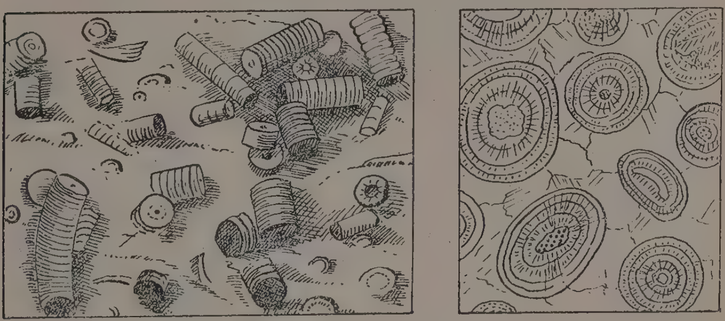
shells, and in some cases it is apparent that the limestone is chiefly made up from such remains: in still more cases, microscopic examination reveals the presence of great numbers of smaller shells of different kinds. In some limestones organic remains are only seen on surfaces that have been exposed to weathering, for in many cases the effect of weathering is to remove the matrix more rapidly than the organic remains themselves are worn away: they thus stand out most prominently on weathered surfaces.

Varieties of limestone are often named after the type of organic remains most abundant in them: we may thus recognise, for example, *shelly limestones* and *coral limestones*. *Crinoidal limestone* is a very important type made up largely of the remains of *crinoids* or "sea-lilies": these organisms are described more fully on p. 184, but it may be mentioned here that they are related to the star fishes and have skeletons consisting of plates made of calcite. In a weathered specimen of crinoidal limestone the plates often stand out, and frequently several plates of the stem which supported the animal are seen in contact (*Fig.* 67a); in a broken surface of crinoidal limestone, however, the plates (usually a little over a quarter-inch across) are broken along cleavage planes and the rock appears coarsely crystalline somewhat like an igneous rock (a test of the hardness of the minerals soon removes any doubt of this). Masses of crinoidal limestone hundreds of feet thick in South Wales and Somerset show that the sea floor was for a long time covered by a dense population of crinoids. Although these organisms are not particularly common at the present day, they have in the past contributed a good deal to the formation of limestones.

An *algal limestone* is one made up largely of the skeletons of *algæ*, that is, of lowly aquatic plants related to seaweeds, which had the power of forming skeletons of calcium carbonate.

Most of these organisms—corals, shells and crinoids—probably lived in water of no very great depth, and some certainly lived in quite shallow water. Moreover, some of the animals were attached firmly to the sea floor (as, for

example, the oysters); and it is unlikely that their remains were carried away from the place where they lived; it is thus apparent that many limestones were formed in comparatively shallow water. The view, once widely held, that limestones had been formed in deep water, is certainly erroneous. Most limestones have been formed in water into which little or no detrital material was being carried from the land. It may be remarked here that, while most limestones are of marine origin, some have been formed in freshwater, in lakes into which little material was being transported and in which organisms with calcareous skeletons were living. Such fresh-water limestones are generally



a b

FIG. 67. a, Crinoidal Limestone, weathered. Carboniferous Limestone, Waterlip, Somerset. Slightly reduced; b, Oolite (Carboniferous Limestone, Bristol) seen in a thin slice under the microscope. Magnified about 20 diameters.

thinner and less widespread than the great masses of limestone of marine origin.

Oolite is a variety of limestone made up of a large number of small spheres of calcium carbonate (*Fig.* 67b): many oolites look much like the roe of a fish (hence the name, meaning roe-stone). In a thin section under the microscope the grains in an oolite are seen to consist of spheres made up of concentric layers. Some oolites when broken split across the spheres, and their structure can be seen with a lens; other oolites have the grains more loosely cemented,

and the fracture often passes round the outside of the grains.

The origin of oolites is not very fully understood. It is certain that they were formed in shallow water, for they often show current bedding: the grains, whatever the mode of formation, were rolled about and deposited by currents. It is probable that the layers of calcium carbonate were formed as a chemical deposit. Some investigators have thought that certain organisms (including algæ) have played a part in their formation, but although algæ are present in many oolites they are absent in others. Oolites are forming at the present time in the shallow waters of the Bahama Bank in the West Indies.

Oolites are frequently used as building stones, especially in the south of England and the east Midlands: they include the Portland Stone and Bath Stone. Many of these stones are known as *freestones*, since they occur in thick beds which can be cut or worked in any direction. The term freestone is also used, especially in Scotland, for sandstones which have this quality.

Pisolite is similar to oolite but has larger grains, often the size of peas. In a pisolite the grains are not always spherical, and are often in the form of flattened spheres.

Chalk is a soft white limestone usually of very fine grain. Many samples of chalk are extremely pure, containing only minute percentages of insoluble matter. The minute shells of some lowly organisms (*foraminifera*, see p. 181) are present in some abundance, but the greater part of the chalk often consists of fine calcareous particles. The similarity of this material to a deep-sea ooze led to the view that much of the chalk had accumulated at great depths, but the occurrence in it of fragments of large shells and of the remains of certain other animals suggests its formation in water of only moderate depth.

All the types of limestone named above consist mainly of calcium carbonate: all include a certain proportion of material insoluble in dilute acid, and many also have a small amount of magnesium carbonate. Limestones containing a high percentage of magnesium carbonate are called magnesian or dolomitic limestones. Those consisting almost

entirely of the mineral dolomite are known as *dolomite-rocks*, or, usually, simply *dolomite* (it is a little confusing, however, to use the same name for a rock as for a mineral, even though the rock consists wholly of that mineral). Dolomite-rocks are often brownish or yellow in colour, but they vary much in appearance, some being rather coarsely crystalline and others extremely fine-grained. They may easily be distinguished from an ordinary limestone since they do not effervesce with cold dilute acid; a small chip warmed in a test-tube with hydrochloric acid presently begins to effervesce and finally dissolves completely. Most dolomite-rocks contain few fossils: this may partly be due to their having been obliterated in the process of the formation of the dolomite, for it is probable that most dolomite-rocks originated as limestones which have subsequently been changed chemically by interaction with magnesian salts, either in the sea-water soon after deposition or in percolating underground waters at a much later date.

Although they are not calcareous rocks, *ironstones* may conveniently be mentioned here. As already noticed in the last chapter, hæmatite commonly occurs in veins and as such is often mined as an ore of iron. In this country, however, most of the iron ores which are being worked are ironstones which are bedded rocks of sedimentary origin. Those of Cleveland (Yorks.) and the east Midlands have an oolitic structure: the oolite-like grains consist of silicate of iron (chamosite) which appear to have been deposited chemically on the sea floor. When exposed at the surface such ironstones are orange or brown in colour, but where they are unweathered (and the iron compounds are unoxidised) they are green. The bedded ironstones found in the Coal Measures, often above the coal seams, were formerly worked with the coal and gave rise to the iron industries of Staffordshire and South Wales: they are only mined in a few places at present, because they occur in small isolated nodules or in beds rarely more than a few inches thick. These Coal Measure ironstones are often called *clay ironstones*, for the iron compound (in this case *siderite*, carbonate of iron) has impregnated the clay in which they occur. Clay ironstones

are thought to have been formed by chemical precipitation from solution, probably in fresh waters.

Carbonaceous Rocks. *Peat* is a carbonaceous rock in which vegetable debris can easily be seen. Peat varies in colour from brown to black and is often loosely compacted. It consists of plant material partly decomposed under water. Usually peat contains a considerable percentage of mud or other impurities. Peats have been formed in badly-drained upland areas and in low coastal or fenland areas. The thickness of the deposit may be over 50 feet and at different levels in this mass, different types of flora corresponding to changes in climate may be found.

Lignite (also known as *brown coal*) is more compact than peat. Very often it shows a distinctly woody structure. Lignite is mined extensively in Europe. It contains a higher percentage of carbon than peat, but a smaller percentage than ordinary coal.

Bituminous coal (including house coal and coking coal) needs little description. Its bedded structure and the occurrence of bright and dull layers should be noted. Plant structure is rarely visible to the naked eye except on some of the dull surfaces, but the presence of various parts of trees in the mass of the coal has now been demonstrated microscopically, although great difficulty was for a long time experienced in grinding sections thin enough to be transparent. Bituminous coals nearly always rest on a rootlet-bed (which is often a fireclay), and they appear to have been formed as a rule from the growth of forests approximately in the places where the coal is now found. In other words, at least a substantial part of any coal seam was formed "*in situ.*"

Cannel coal, on the other hand, appears to have been formed by the drifting of vegetation for some distance from its source; cannel does not rest on a rootlet-bed and occurs in beds which are less continuous than the seams of bituminous coal. Occasionally it encloses fossil animals; these are absent from bituminous coal, and animals were evidently unable to live in the swamps where bituminous coal was being formed. Cannel may be recognised by its compact-

ness, by its smooth conchoidal fracture and by its not soiling the fingers. It burns with a clear flame, and was formerly much valued for adding to ordinary coal in gas manufacture as it increased the illuminating power of the flame of a gas jet; with the use of incandescent mantles (and the requirement therefore of heating power rather than of a luminous flame) cannel has lost its importance.

Anthracite is another coal with a conchoidal fracture but it is distinguished from cannel by its lustre and by the fact that it burns with practically no flame; this is because it is very poor in volatile constituents, while it contains the highest percentage of carbon of all coals (in many anthracites carbon forms 90 per cent. or more). Anthracite occurs in continuous seams overlying fireclays, and it is to be thought of as more closely related to bituminous than to cannel coal; microscopically it shows similar constituents to bituminous coal (these have been seen only by examination of polished surfaces of anthracite as it is so opaque that no section has yet been made thin enough to be transparent). In South Wales where the most important British anthracites occur, the bituminous seams become gradually richer in carbon as they are traced into the anthracite area.

On the whole, peats are of comparatively recent date, lignites rather older, and bituminous coals still older. The latter have been formed at several different periods, however, since the appearance of land vegetation on the earth.

Siliceous Rocks. Flint and chert, which are the only forms of siliceous rock, have already been mentioned (p. 99). They consist of minutely crystalline silica occurring in beds or nodules. *Chert* often occurs in limestones. In some cherts there are bands of fossil shells and crinoids, the skeletons of which must formerly have been composed of calcium carbonate, but which are now represented by silica. It thus appears that such cherts have been formed subsequently to the deposition of the limestone, by the chemical replacement of calcium carbonate by silica, which must have been introduced in solution. Other cherts have been formed more directly from the remains of small marine organisms which had a skeleton of silica (*Radiolaria*, p. 181), while

still others are thought to have been formed partly by a chemical precipitation of silica on the sea floor independently of organisms.

Flint is mostly confined to the Chalk. Occasionally flints enclose fossils such as sponges or sea urchins (echinoids, p. 184), but the irregular shapes of many flints are quite independent of any organic structure. The replacement of the calcium carbonate of shells shows that the flints, like certain cherts, have been formed subsequently to the rock enclosing them. In the case of the Chalk flints it is thought that the silica has been obtained from scattered remains of siliceous sponges which are fairly abundant in the Chalk: these must have been dissolved and the silica re-deposited from solution.

Concretions. Concretions are more or less spherical or irregular masses, varying from a few inches to several feet in diameter, which consist of material of different nature from the surrounding rock brought together by percolating waters: in many cases the material was scattered through the rock and has been collected together. Thus flints may be regarded as concretions. In other rocks (especially in clays and shales) concretions of iron carbonate and of calcium carbonate may be found. Some of the clay ironstones of the Coal Measures are at least partly concretionary. Like some concretions of calcium carbonate, these often form *septaria:* in these a series of internal cracks is present, commonly filled up later by the deposition of minerals (particularly calcite). When such a nodule is exposed to weathering, the material of the nodule may disintegrate more rapidly than the vein-filling, so that the "cracks" stand out as plates (hence the name septaria, from *septum,* a plate).

SUGGESTIONS FOR PRACTICAL WORK

Besides samples of rocks in a reference collection, other specimens should be available for breaking up and for various tests. A very useful understanding of many rocks is gained by breaking them into grains or crushing to a powder.

The approximate grain sizes of sandstones and shales may be determined by sieves or simple elutriation. The separation of the sandy part of coarse shales, or of the insoluble residue from various

limestones (and the examination of its character) should be carried out. Effect of cold and hot acid on limestones, dolomite, and ironstones.

If a microscope is available students may learn to make their own thin sections from "easy" rocks, by rubbing down chips of the rocks. Quite good work has been done by grinding on pieces of flagstone.

QUESTIONS

1. How would you distinguish between dolomite, limestone, quartzite?
2. Write an account of the different types of rock that owe their origin to living organisms. (C.W.B.Hr., 1935.)
3. Explain concisely the characters of the following rocks:
   flagstone, crinoidal limestone, shale, lignite, chert.
   Where may examples of each be found?
4. State the mode of origin of each of the following:
   fireclay, oolite, breccia, cannel coal, flint.
   Mention localities where each occurs and state any economic purposes for which they are used.
5. Describe briefly the chief types of deposit that were accumulated on the floors of shallow seas. In what respects do they differ from deposits laid down in deep waters? (C.W.B., 1933.)

CHAPTER VIII

THE ARRANGEMENT OF THE SEDIMENTARY ROCKS.—I

The stratified arrangement of the sedimentary rocks has already been pointed out in Chapter I. It was then noted that most of the sediments were laid down in more or less horizontal beds, but that many of them have since been tilted so that they now dip to varying amounts.

Lamination. In some strata there is a very obvious arrangement of the material in quite thin layers, so that a large number of visible layers make up a single bed. Such a stratum is said to be laminated. A laminated rock can usually be split into thin sheets; a paper shale (p. 116) is an excellent example, but many sandstones and limestones are also laminated. The lamination often results from the occurrence of successive layers of slightly different material, or from the presence of minerals (such as flakes of mica) arranged with their axes along the bedding planes.

Lamination is ordinarily parallel to the stratification, but in some sandstones and oolites the lamination is inclined obliquely to the bedding planes; it is then known as *oblique lamination*. The formation of oblique laminæ in a horizontal bed will be understood from *Fig*. 68, where a current from the left may be supposed to be transporting material: in the shallow water on the left the current is too powerful to allow any material to accumulate, but the grains are, so to speak, "tipped" over the edge into deeper water much as rubbish is tipped from a truck on a pit bank. It will be noted that the resulting arrangement of the laminæ is something like that in a sand dune (p. 24). In water-laid deposits this type of structure is produced only by current action in shallow water, and is sometimes known as

current bedding. It is characteristic of deltaic deposits. In such deposits, since the direction of the currents may frequently be changed, the lamination of successive layers may be inclined in different directions.

Current-bedded deposits frequently show other evidences of shallow water origin. One type of evidence is the existence of *wash-outs,* or stream channels (filled in with later deposits) cut through or into the stratum (*Fig.* 69). It will be noticed that observations of dip have to be taken with care when only small exposure of current-bedded rock are available, for quite incorrect readings may be made if planes of oblique lamination are taken for true bedding.

Jointing. The occurrence and spacing of joint-planes in both sedimentary and igneous rocks are of much import-

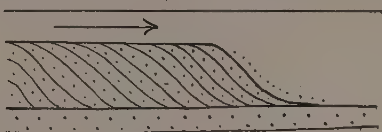


FIG. 68. Diagram to show a mode of origin of oblique lamination. Arrow shows direction of current carrying material.

ance in quarrying operations and in determining the sizes of blocks which can be quarried. Some of the joints cut through only one stratum, while others (the *master-joints*) extend through great thicknesses of rock. The discontinuous joints are usually most frequent in limestones and sandstones, least frequent in clays and shales: indeed, the more consolidated rocks in general have the best marked joints.

The origin of jointing in sedimentary rocks is not easily explained, but it may be partly due to shrinkage and partly to movements in the earth's crust. Frequently the faces of joint planes show evidence of these movements for they are marked by a series of parallel scratches or striæ, known as *slickensides,* which have been produced by the rubbing together of the sides of the joint plane. The relation of

joint planes to earth movement is still more forcibly illustrated by the joint planes in many conglomerates, where they pass straight through the pebbles (however hard), not around them: it will be seen from *Fig.* 70 that such a condition would allow free movements within the bed, whereas a parting which traversed the rock keeping outside the pebbles (*Fig.* 70, x) would leave the sides "locked" together.

Joints are of great importance in allowing the flow of underground waters, and often joint planes (especially in calcareous rocks) have been widened by solution. In many cases, too, the joints have become coated with mineral de-

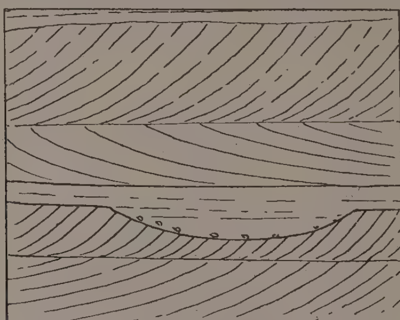


FIG. 69. Oblique lamination in sandstone, with a wash-out. Bunter Sandstone, near Nottingham. Length of section about 12 feet.

posits carried by percolating water, or the rock adjoining the joints has been altered chemically.

Dip and Strike. The dip of a stratum is its inclination, measured by the angle between the stratum and the horizontal. In *Fig.* 71 a boy is seen sliding down the slope made by an inclined bedding plane in a limestone quarry: the marks made by his earlier slides are seen in the figure. When he slides down this surface he naturally follows the steepest slope (as water would if it were poured out at the top), and if he started at any other point he would slide down in a direction parallel to that shown. While he keeps to those directions he is taking the steepest slopes on that

bed of rock. These represent the *true dip* of the bed. If he crawled across the bed at an angle to the marks he would be following a less steep slope: if he followed the dotted line (or any other line parallel to it) he would be keeping quite level all the time. The dotted line marks the *strike* line drawn on the bed, and is at right angles to the direction of maximum dip (*true dip*). If the reader can visit a quarry showing a dipping bedding plane in this way he will find it helpful to spend some time examining these facts: it is useful to mark with chalk the directions of strike and true dip, and to measure the dip. However steeply the bed is dipping it will be observed that horizontal lines can be drawn on the face of the bed; every such line is a strike line. Strike may be thought of as the direction in which the bed extends horizontally; it must be remembered that most beds do

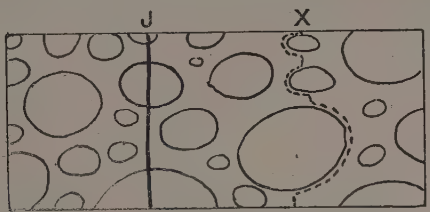


FIG. 70. Diagram to show joint (J) in a conglomerate.

extend (or formerly used to, if parts have been denuded) for miles in the direction of strike.

If no suitable quarry is available for study, a good idea of the problem can be gained by using an inclined book or a black board as a bedding plane.

A miner calls the strike direction the *level-course;* obviously a gallery driven in a seam along this direction would be level. The underground roads in many pits form two series at right angles, those following the strike and those following the dip.

Referring again to *Fig.* 71, it will be noticed that two sets of joints have been shown: one set consists of dip joints and the other of strike joints.

Measurement of Dip. Dip is measured by means of a simple instrument known as a *clinometer* (*Fig.* 72) which

consists essentially of a protractor with a pendulum freely swinging from its centre. If the horizontal rest is placed on a bedding plane in the direction of true dip, the amount of inclination is indicated by the pendulum. By turning the clinometer away from the direction of true dip towards the strike it can be verified that the inclination steadily decreases. In making a reading of dip by resting the clinometer on the rock in this way it is of course necessary first to make sure that the bedding plane is quite smooth. If the surface is too irregular to give an accurate reading, the

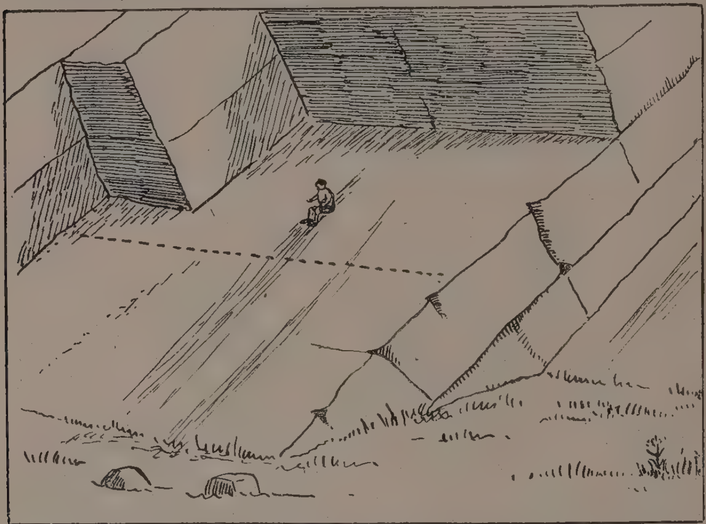


FIG. 71. Part of a quarry showing dip and strike. The boy is sliding down the true dip on a bedding plane; the dotted line shows the direction of strike.

clinometer may be held up at a little distance from the section in such a way that the straight edge of the instrument coincides with the dip.

The dip is thus known in degrees, and it is usual to record it on a map by drawing a single arrow (see *Fig.* 84) pointing in the direction of true dip and entering the angle beside it: the point of the arrow should be at the spot where

the reading was made.[1] It is sometimes convenient to record the dip in terms of gradient of the bed, for instance as 1 in 3, where 1 unit represents the distance the bed falls in 3 units of *horizontal* distance (not measured on the bed): the ratio 1/3 is the tangent of the angle of dip, so that the two types of record may be interchanged if a tangent table is used.

In making dip observations it is always necessary to examine closely the section to be measured. It is never safe

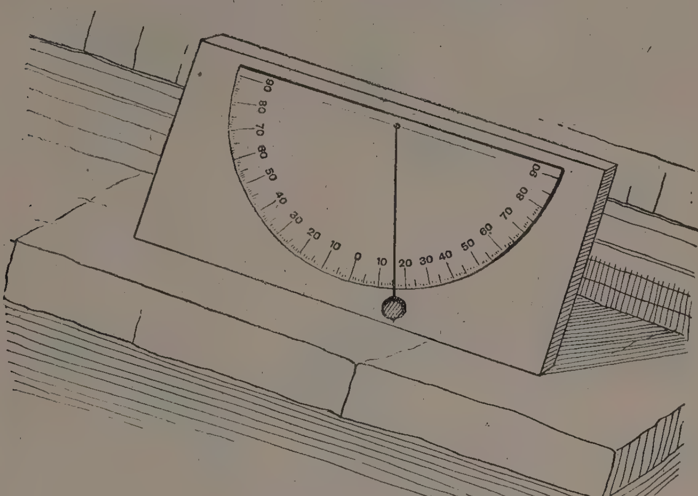


FIG. 72. A simple home-made Clinometer.

to stand some hundreds of yards away from a cliff or quarry and to decide the dip from that distance. This will be appreciated when it is realised that a cutting made along the direction of the strike of dipping rocks will show the beds running horizontally along the cutting: only if the rocks are cut in the direction of true dip will the real angle of dip be seen in such a distant view. Sections cut obliquely to this show only an *apparent dip*. The distinction is illustrated in the diagrams in *Fig*. 73: in *Fig*. 73a the front of

[1]The symbols for horizontal and vertical beds are shown in *Figs*. 76 and 77.

the block shows the strike and the sides the true dip (since they are at right angles); in *Fig.* 73c all the sides show apparent dips, and the block would need to be cut perpendicularly to the strike to show the true dip. Given the direction and amounts of two apparent dips, it is possible to calculate the true dip, but this is rarely necessary, for a close examination of any section will generally reveal projecting

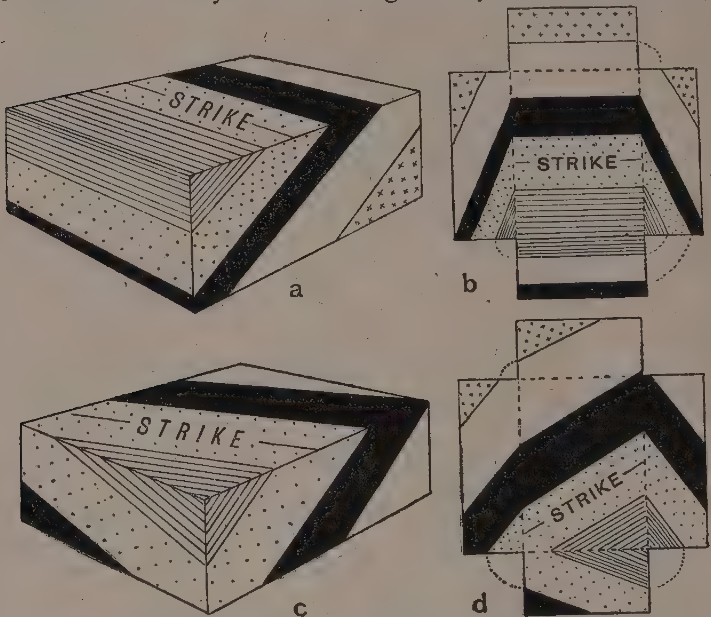


FIG. 73. Block diagrams to illustrate dip and strike. a, with two sides showing true dip, the strike parallel to the front edge; c, with all sides showing apparent dips; b and d, outlines for construction of the models.

corners of bedding planes where true dip can be read. In the rest of this chapter where "dip" is mentioned it refers to true dip.

Outcrop. The *outcrop* is the edge of the stratum which appears at the surface (or which is immediately beneath the soil). If the ground is horizontal, the outcrop

runs across the country in the direction of the strike (*Fig.* 73a): thus the strike coincides with the general direction of the outcrop. Of course the ground is rarely horizontal for any long distance, but still in many areas the average elevation changes so little in relation to horizontal distance, that, although the outcrop and strike do not always agree in detail, in a general way there is a fairly close agreement. If we look at a geological map of England the outcrop of the rocks from Yorkshire to Dorset gives us the direction of strike, and the dip must be at right angles to this.

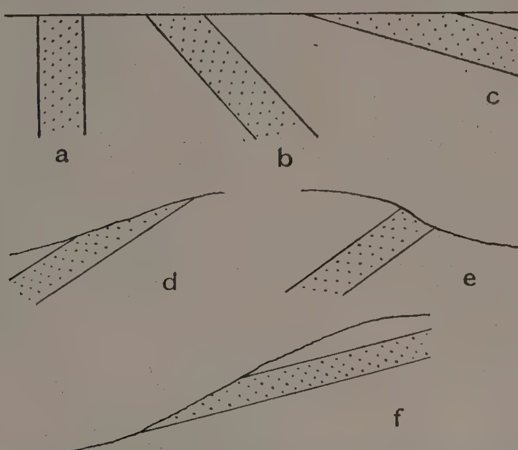


FIG. 74. Diagram to show the variation in the width of outcrop with varying dips and slope of ground.

The width of the outcrop of a given stratum or group of strata depends first of all on its thickness, and also on the amount of dip and the slope of the ground: the greater the amount of dip the narrower the outcrop of the same bed (*Fig.* 74).

It is desirable for the student to become acquainted as soon as possible with simple geological maps. The block models which illustrate this chapter show simple geological maps on their upper faces; in these the outcrops are straight

because the ground is represented as quite level. When the ground is uneven various other modifications are introduced.

The effects of varying contour are best understood by considering first a simple area in which the rocks are horizontal (*Fig.* 76). It may be supposed that a piece of country made up of horizontal beds of shale, sandstone and limestone has been subjected to denudation, and valleys have been cut by rivers. The highest bed (the limestone) naturally has been most affected, and has been removed from much of the area; the lowest bed (the shales) has been reached only in the deepest parts of the valleys. A well sunk anywhere on the limestone would reach first sandstone and then shale. The pattern of the outcrops may be understood best by remembering that each bed, being horizontal, keeps at a uniform height above sea level; the top and bottom of each bed actually form contour lines where they intersect the surface, but of course they are not necessarily lines at 100 foot or 50 foot intervals above the sea. The base of the limestone forms the 400 foot contour in *Fig.* 76, but the base of the sandstone is everywhere at 115 feet. The essential thing to remember is that the outcrops of horizontal beds give the same kind of pattern as contour lines.

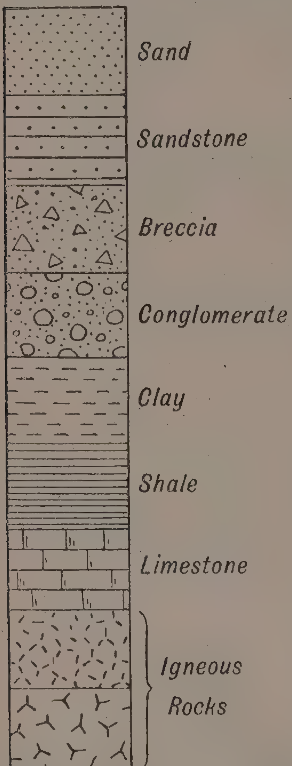


FIG. 75. Types of shading to represent rocks in geological sections.

This may be contrasted with a case in which the strata are vertical, when the outcrops are straight, whatever the form of the ground (*Fig.* 77). This case is easily understood

by taking a number of books and standing them on edge side by side to represent vertical beds; if now a river is supposed to cut a valley into the upper edges, whatever its pattern it will not affect the straightness of the covers of the books as they are seen from above.

Rocks are only rarely quite horizontal or quite vertical, but often they are either gently dipping or steeply dipping, and the two extreme cases illustrated indicate the general

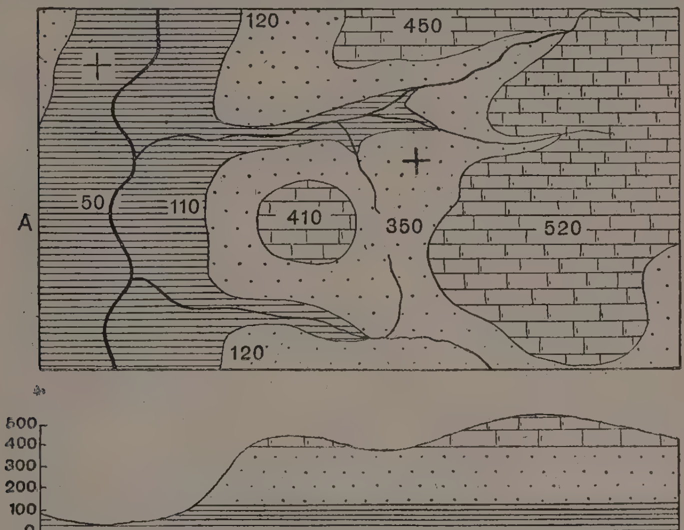


FIG. 76. Geological map of an area with horizontal rocks. The section below is drawn from A to B.

character of the outcrops in these two types of case. When the rocks are gently dipping and the country is cut into hills and valleys, the outcrops are sinuous, and tend more or less to resemble contours: when the rocks are steeply dipping the outcrops are almost straight whatever the form of the land may be.

Geological Sections. The student should begin the drawing of sections across geological maps as soon as possible, for it is most important to acquire facility in inter-

preting maps. He should aim at being able to produce neatly drawn sections. Sections may be drawn across the maps shown in *Figs*. 76 and 77 along several different lines in each case. When contours are given, a profile representing the form of the ground should first be drawn on a scale with as little vertical exaggeration as is convenient; if gently dipping beds are to be shown, some exaggeration is unavoidable, but no exaggeration is needed if the beds are all dipping steeply.

The positions of the outcrops of the various beds should be marked off on the profile. In drawing the strata on the

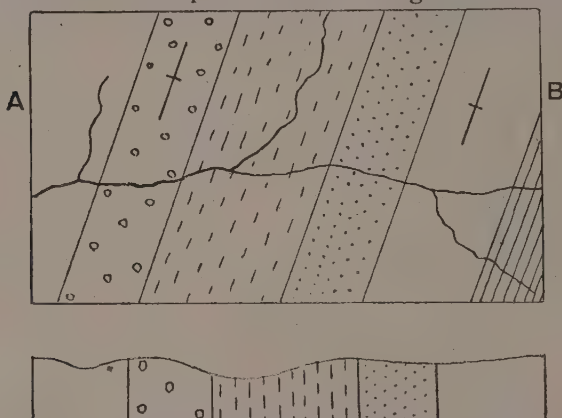


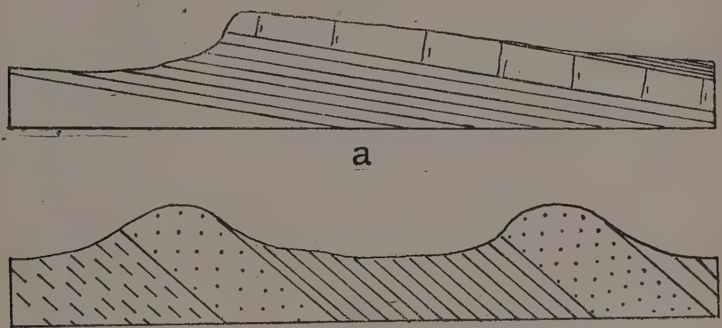
FIG. 77. Geological map of an area with vertical rocks. The section below is drawn from A to B.

section it is most important to remember that the sequence or succession must be such that the oldest rocks appear underneath the newer rocks. If the rocks are dipping the newer rocks will ordinarily lie in the direction *towards* which the rocks are dipping, for the older bed will always pass under the newer one.

Where a section is in the direction of true dip the angle of dip given on the map is the angle to be used: a section cut obliquely to the dip will show an apparent dip which always must be smaller than the true dip.

In finishing off a section it is useful (besides colouring it) to introduce some shading to show the nature of the rocks (as shown in *Fig.* 75). It is desirable to arrange this shading so that it runs with the bedding (as in the various diagrams illustrating this book) and not obliquely to it. This gives a better idea of the structure and avoids confusion which might otherwise arise.

Escarpments. Every piece of country made up of dipping strata is marked by successive outcrops of different rocks. Some of these rocks are softer (or more rapidly



a

b

FIG. 78. a, Typical escarpment formed by gently dipping limestone between shales; b, Escarpments formed by steeply dipping beds.

eroded) than others, and it is frequently found that the outcrops of the less resistant rocks (generally the clays and shales) tend to form lower ground than the outcrops of such rocks as sandstones and limestones. These often stand out as ridges, running across the country in the direction of the strike.

Such ridges are known as *escarpments*. They have a structure like those shown in *Fig.* 78a. A more resistant bed is flanked on either side by less resistant groups; on the one side, facing against the dip, the ridge is steep (the *scarp slope*), while on the other (*the dip slope*) it agrees approximately with the dip. Hills having this structure are abun-

dant in many parts of Britain, and practically all the hills are of this type in south and east England.

The scarp slope is kept steep by the rapid weathering of the soft beds and by the consequent undermining of the resistant bed; the dip slope is formed by the removal of the overlying softer beds down to the resistant band, so that the dip tends to determine the slope on that side. If the dip is gentle the dip slope is usually gentle, while if the dip is great the dip slope is steep; the hill then becomes a "*hog's back*" (*Fig.* 78b).

SUGGESTIONS FOR PRACTICAL WORK

Most of the practical work will relate to geological maps; work may be begun by exercises on maps like those given in the text, but there is no reason why students should not use actual maps for section drawing at a very early stage. The Geological Survey map of Britain on the scale of 25 miles to an inch is useful for drawing general sections across parts of the east of England. On many 1 inch maps (of areas with uniformly dipping or nearly horizontal rocks) suitable section lines can also be chosen for the beginner. The use of these "real" maps greatly increases the interest of the work.

Other work which may be undertaken includes the making of block models (like those illustrated in *Fig.* 73); plasticine may also be used, moulded to form hills and valleys, to show patterns of outcrops (represented by inclined sheets of tin or card).

Students may also construct a simple clinometer, and study changes of dip in different directions on an inclined bedding plane (or on a book).

QUESTIONS

1. What is meant by the term outcrop? By the assistance of sketches show how the width of an outcrop is affected by the dip of strata and by the slope of the ground. (C.W.B.Hr., 1936.)
2. Explain what is meant by *true* and *apparent* dip, and the differences between them. (C.W.B.Hr., 1933.)
3. In a region of level ground three pits are sunk to the same coal seam, at A, B and C. B is 500 yards east of A, and C 500 yards south of A. In both A and B the seam was met 100 feet down, but in C it is 600 feet down. Draw a map of the area to a convenient scale, and mark on the map the directions of dip and strike. Find, graphically or otherwise, the amount of dip.
4. Explain the importance of bedding, jointing and dip in relation to the mining and quarrying of rocks.
5. What characters would you expect to observe in sediments of shallow-water origin?

CHAPTER IX

THE ARRANGEMENT OF THE SEDIMENTARY ROCKS.—II.

Folding. Strata rarely continue for many miles with the same angle of dip. The dip may continue in the same general direction with slight variations of angle or the direction of dip may change completely.

Such rapid changes of dip are normally found in folded rocks. The folding of sedimentary rocks has generally resulted from the lateral compression of the earth's crust. The rocks shown in *Fig.* 79 clearly take up less area on the earth's surface after they have been folded: the same may be demonstrated by crumpling a pile of papers. The causes of the movements in the earth's crust which led to the compression do not concern us here; there is no doubt as to the fact that rocks have been folded and that the folding has reduced the area they occupy on the surface of the globe. Probably the folding took place very slowly.

In a series of folded rocks two main elements can at once be distinguished: there are upfolds or *anticlines* (where the beds are inclined away from one another), and downfolds or *synclines* (where they are inclined towards each other). It may be supposed that at one time each anticline formed a ridge, and each syncline a valley, but folded country rarely shows these features, for many folds were formed long ago and have been subjected to weathering and other denuding agencies for so long that the upraised portions have been worn down and may form fairly level surfaces; not infrequently the anticlines are worn down below the level of the synclines (*Fig.* 80b). In the middle of a syncline rocks newer than those on the flanks outcrop: in the middle of an anticline, rocks which are older.

The folds shown in *Fig.* 80 have similar dips in the two sides (or *limbs*) of each fold: they are *symmetrical* folds. In an *asymmetrical* fold the dip in one limb is greater than that in the other (in *Figs.* 81a and b it is greater at B than at A and C). Asymmetry may be so marked that one limb may be overturned and the rocks in it *inverted*, the newer rocks being there under the older (as at B in *Fig.* 81b). Such folds with inverted limbs are characteristic of regions where the pressure producing the folding has been very intense: they are known as *overfolds*. Overfolds which are completely turned over so that one fold seems to lie on

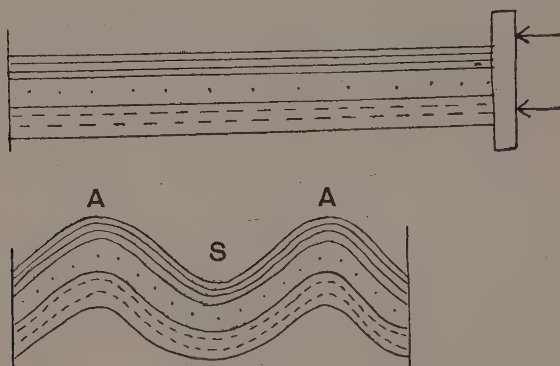


FIG. 79. Diagram to show the shortening of an area of horizontal rocks by folding. Arrows show direction of pressure.

another are called *recumbent folds* (*Fig.* 81c). Recumbent folds of great extent occur in the Scottish Highlands, and there it is often difficult to determine which of the beds are the right way up and which are inverted.

Although overfolds are of great interest as evidence of the intensity of the lateral pressures which produced many folded mountain chains, it is not necessary for us to be concerned with their appearance on geological maps. The appearance on maps of the simpler types of fold is very important. Some of these are illustrated in *Fig.* 82. In a symmetrical fold, since it has similar dips in the two limbs,

any group of strata will have outcrops of equal width in the two limbs if the ground is horizontal: in an unsymmetrical fold, the steeper dip of one limb will be indicated by the narrower outcrops in that limb.

The fold shown in *Fig.* 82a has outcrops which remain parallel as they are traced across country. In *Fig.* 82b a somewhat similar fold is shown in which the outcrops curve over on the surface and unite: this is a *pitching syncline*. The difference between folds with or without pitch may easily be represented by folding a sheet of thin card to form

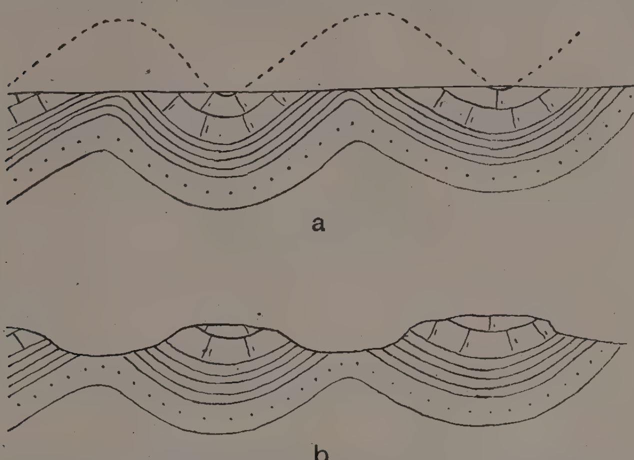


FIG. 80. Symmetrical denuded folds. a, with flat ground, dotted line showing original extent of the rocks; b, anticlines worn lower than the synclines.

a simple syncline; if the curve of the fold is allowed to rest on the bench for its whole length it has no pitch, but if the fold is tilted without altering its shape so that only one end of the card rests on the bench it is a pitching fold, and its outcrop on a more or less horizontal surface may be imagined (*Fig.* 83). In *Fig.* 82b the inclined line running through the block shows the direction and amount of pitch. It should be noticed that in the direction of pitch the outcrops in a syncline become further apart and newer beds

come in, while in a pitching anticline the outcrops come together and older beds disappear in the direction of pitch. A group of pitching folds is shown in *Fig.* 84; the student will find it useful to construct several sections along parallel lines across this map.

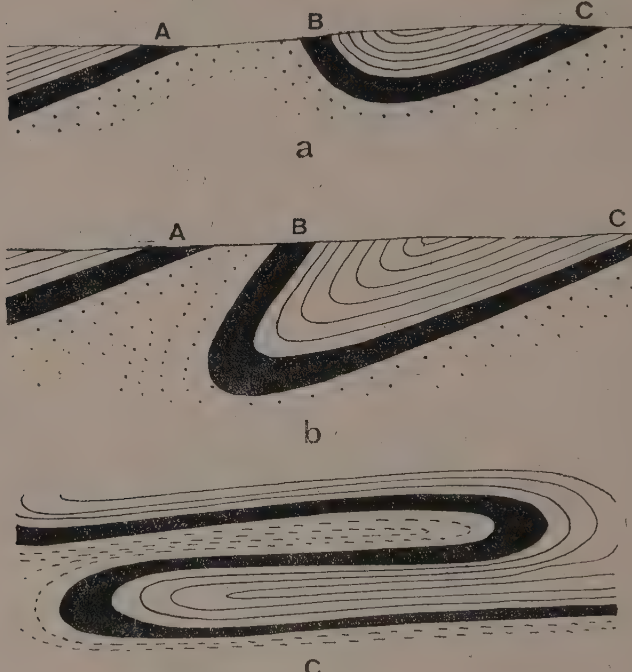


FIG. 81. Asymmetrical Folds. a, simple asymmetrical folds without inversion; b, overfolds with inverted rocks at B; c, recumbent folds.

Folds vary greatly in size. It is possible to see several distinct folds in the space of a single quarry, but the more important folds are some miles across. The London Basin and the South Wales Coalfield (*Fig.* 118a) are typical syn-

clines of large size, while the Mendips, the Weald (*Fig.* 119b) and the Pennines (*Fig.* 118b) are anticlines.

Two other types of fold should be known by name. A *monocline* is in a way simpler than an anticline or syncline; it is caused by a sudden increase of dip followed by a return to the horizontal or gently inclined position shown generally in the area (*Fig.* 85). A monoclinal fold extends through the middle of the Isle of Wight. A *dome* is an anticlinal structure in which the dips are outwards in every direction: the outcrops seen on a map are more or less circular. The Harlech Dome in Merionethshire (North Wales) is a good example.

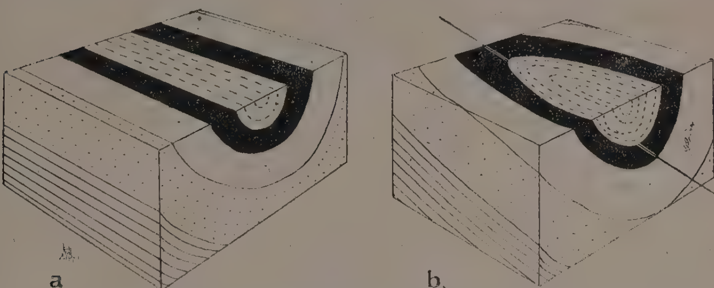


FIG. 82. Block models of symmetrical synclines. a, without pitch; b, with pitch, inclined line showing amount and direction of pitch.

Faults. A *fault* may be defined as a fracture in the earth's crust along which there has been movement. Strata may be seen to end abruptly at a fault, and any bed so interrupted will appear on the other side of the fault either higher or lower than before. There are several different types of fault but particular attention may first be directed to those known as *normal faults*, such as that illustrated in *Fig.* 86. Here the fault plane is steeply inclined: the angle between the fault plane and the vertical is the *hade* of the fault (note that hade is measured from the vertical, not like dip, from the horizontal). On one side of the fault (the left in the figure) the beds appear to have sunk relatively to those on the other: we thus distinguish the *downthrown* side from

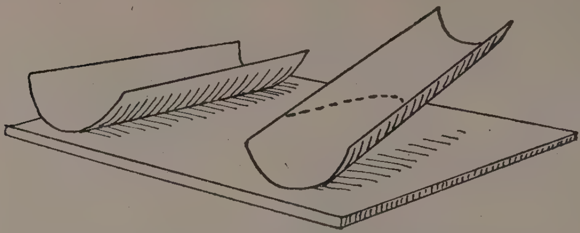


FIG. 83. Folded cards to illustrate the nature of pitch: the pitching fold on the right is marked with a dotted line to show pattern of its outcrop on a horizontal surface.

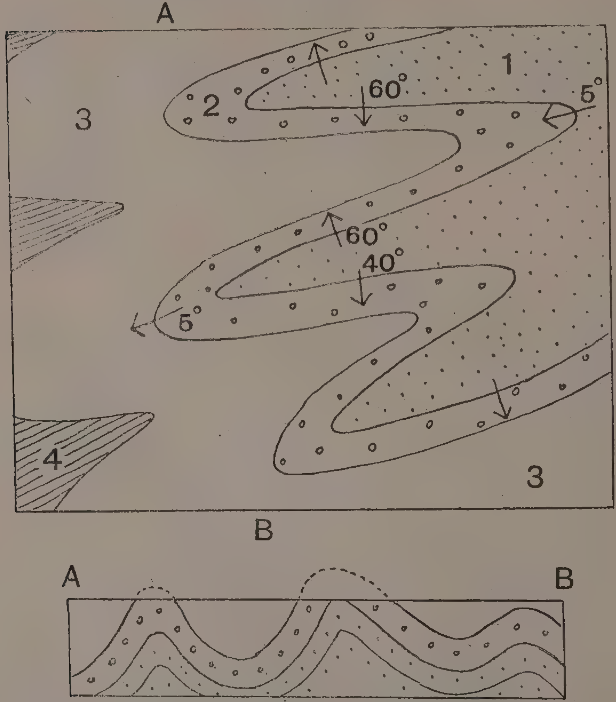


FIG. 84. A Geological Map showing pitching folds. Section from A to B below.

the *upthrown* side. It is by no means certain in any fault that the two sides have moved in opposite ways, and these terms are only relative. It will be noticed that the hade is towards the downthrown side; this is the condition characteristic of normal faults.

The vertical distance separating the two broken ends is called the *throw* of the fault. Note that this is not a distance measured *along* the fault plane, which would, of course, be greater than the vertical distance. The amount of throw of a fault may vary from inches to thousands of feet. Faults with small throw are often exposed in quarries, but the greater faults are rarely seen in sections, and their presence is inferred from other evidence.

Sometimes a fault plane appears like a clean cut through the rocks; if we examine the face we may often find traces

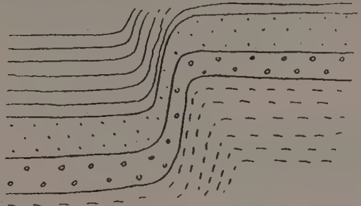


FIG. 85. A Monocline, seen in section.

of slickensides showing the direction of the movement. In many cases the ends of some of the beds tend to turn slightly in the direction of movement (*Fig.* 86). This feature is of great importance to a miner who reaches a fault in the course of working a coal seam, as it enables him to decide whether he must seek upwards or downwards to find its continuation. The bending of the strata also helps to show how such a fault may be regarded as a development from a monoclinal fold; the beds may be pinched out in the steep limb of a monocline (*Fig.* 85), and by further movement the fold may pass into a fault.

In some fault planes there are masses of broken rock consisting of angular fragments torn off from the sides of the fracture: these form a *fault-breccia*.

On a map a normal fault appears as an almost straight line, which marks the line of outcrop of the steeply inclined fault plane (a steeply inclined plane, like a steeply dipping bed, has a nearly straight outcrop). A fault is shown on a geological map by a heavy line, on a coloured map often in white or blue. Sometimes a small mark is placed alongside the line to show the downthrown side.

The presence of faulting is also made apparent on a map by the interruption of the regular arrangement of the outcrops. In order to explain the effects of faults on out-

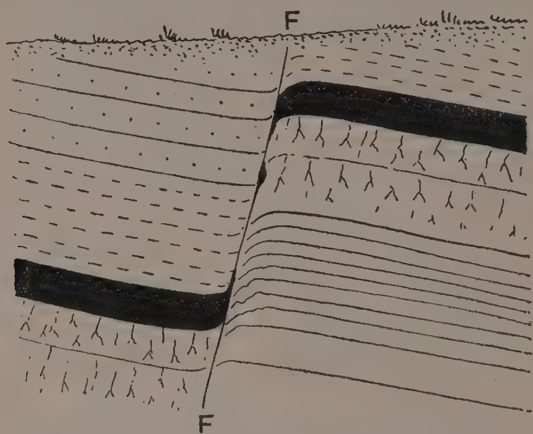


FIG. 86. A Normal Fault, seen in section.

crops it is useful to consider two cases, first of faults which extend in the same direction as the dip, and secondly of others whose direction is that of the strike: the first are known as *dip-faults*, the second as *strike-faults*.

A dip fault interrupts the outcrop of a bed, which is continued along a line in front of or behind its former line (*Fig*. 87c). That such a change is produced merely by raising or lowering one side of the fault is easily understood if a block model is constructed like that shown in *Fig*. 87a; the removal of the upper part of the upthrown side makes it possible to "denude" the area down to one level (as has

actually happened in nature on a large scale). A dip fault cutting across folds has similar effects, save that the outcrops of opposite sides of a fold appear (owing to the different directions of dip) to be moved in opposite directions (*Fig.* 88); thus the upthrown side of a fault cutting across

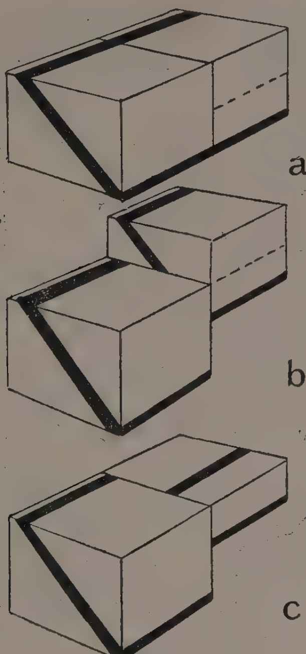


FIG. 87. Diagram to show the effect of a dip fault on outcrops.

a syncline shows a narrowing of the fold (which would be expected since the fold becomes narrower with increasing depth, and the upthrown side brings a deeper part of the syncline level with a shallower and wider part). The upthrown part of an anticline shows a greater separation of the outcrops.

Strike faults affect outcrops in two ways, according to whether they throw in the same or opposite direction to the dip. If a fault throws in an opposite direction to the dip, it has the effect of raising a bed which had been carried down below ground by the dip, and thus causes a repetition

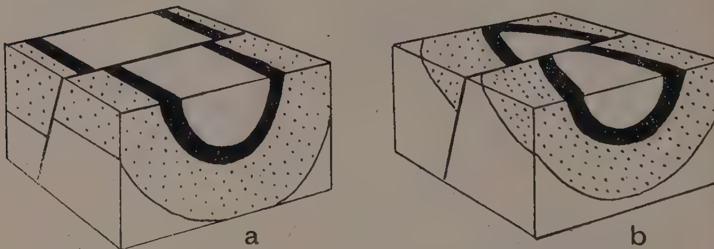


FIG. 88. Block diagrams to show dip faults cutting folds. a, a faulted syncline with no pitch; b, a faulted pitching syncline.

of its outcrop (*Fig.* 89a); if it throws in the same way as the dip it may be said to help the dip to get the beds below ground more quickly, and thus it prevents some beds being seen at the surface at all (*Fig.* 89b).

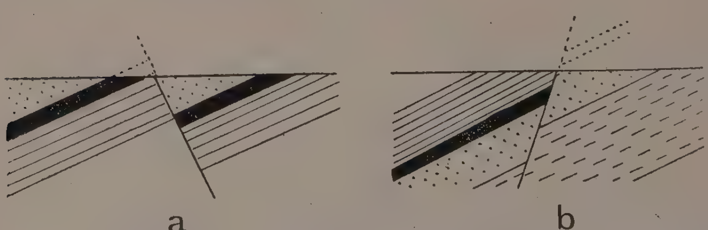


FIG. 89. Effect of strike faults on outcrops. a, throwing against the dip; b, throwing with the dip.

In drawing sections across normal faults it is well to remember that the fault should be shown with a steep hade directed towards the downthrown side: the downthrow may always be determined from the map because at some point along the fault the map will show two rocks of different age

in contact on opposite sides of the fault line: the side where the *newer* rocks occur is the downthrown side.

The faults in any area usually fall into systems with faults more or less parallel to one another; doubtless they were produced by the same earth movements. Some groups of faults have been given special names. When two or more faults throw in the same direction they form what are called *step-faults* (*Fig*. 90a); when two faults throw towards one another they are *trough-faults* (*Fig*. 90b).

Faults of other kinds than normal faults call for very brief mention only. A *reversed fault* differs from a normal fault in having its hade towards the upthrow (*Fig*. 91b). It may be noticed that a pit sunk through this area would pass

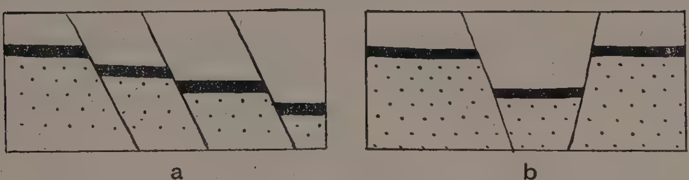


FIG. 90. a, Step faults; b, Trough fault.

through the same bed twice (whereas a pit sunk in the area of the normal fault in *Fig*. 86 might miss the coal seam altogether). Reversed faults, like folds, are generally the result of compressive forces and represent a certain amount of reduction in the surface area covered by the rocks. For this reason the fault planes in reversed faults often have a larger angle of hade; they may be thought of as inclined planes up which the overlying mass has been forced. A reversed fault with a high angle of hade is often called an *overthrust* or a *thrust*. These are only found in areas where there has been intense folding on a large scale. In north-west Scotland are thrusts in which the overlying rocks must have been pushed miles almost horizontally over the gently inclined thrust planes (*Fig*. 91c). Large scale thrusts are often associated with recumbent folds, of which some represent a further development.

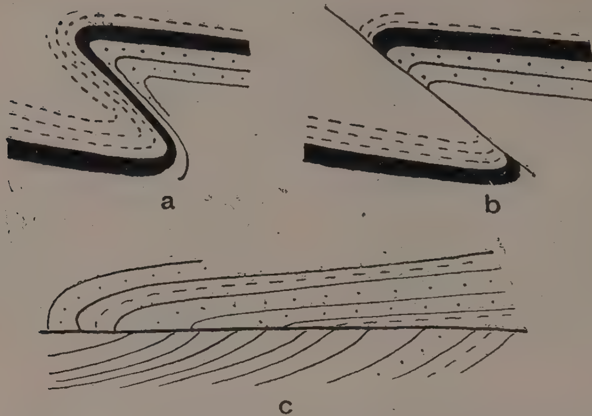


FIG. 91. a, overfold; b, a reversed fault developed from an overfold; c, an overthrust.

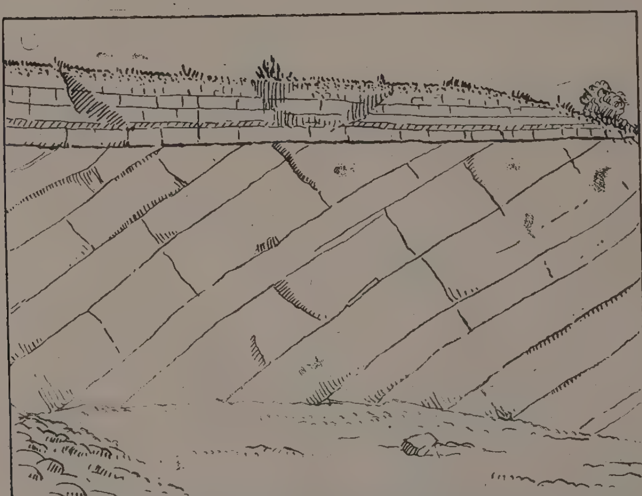


FIG. 92. An Unconformity, Vallis Vale, Somerset. Horizontal Jurassic rocks on dipping Carboniferous Limestone.

Unconformity. Where one rock rests on the worn and denuded edges of another rock or group of rocks, the relation between them is said to be one of *unconformity,* and the upper rock is said to lie *unconformably* on the lower group (*Fig.* 92). Hitherto we have dealt with *conformable* rocks, which may be regarded as having been laid down one above the other without interruption. Unconformity results from an interruption in the sequence of deposits, and marks an interval during which no deposit was accumulating at the place where the unconformity is found, and during which

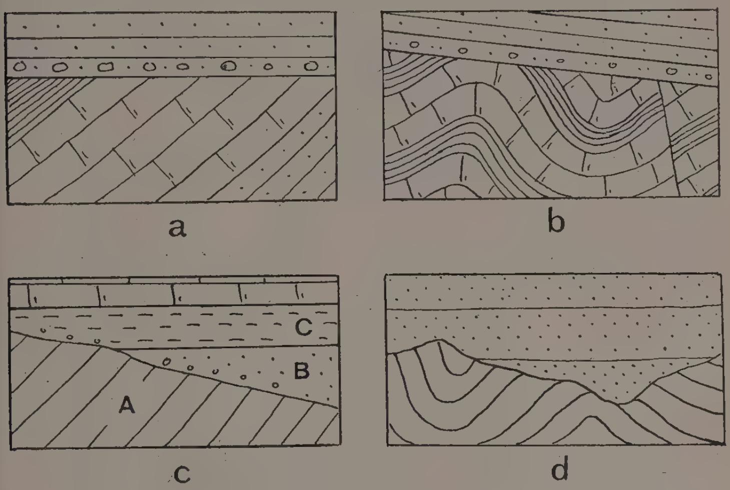


FIG. 93. Sections to show Unconformity. c and d show overlap.

some of the rocks already formed were denuded. The interval may have been only very short, or it may represent a period of millions of years.

An unconformity may be recognised in several ways. Commonly the bed above the unconformity is a conglomerate containing pebbles or boulders which include fragments of rock derived by the denudation of the underlying rocks; this is a very sure indication that denudation occurred between the periods of deposition of the two rocks. In

many cases there is a difference of dip between the beds above and the beds below, the beds above having a more gentle dip than those below. Often the beds below have been folded while those above rest on the worn surface of the folds. Faulting may also affect the beds below and may stop short at the newer beds. In these cases it is clear that the folding or faulting must have occurred at a time before

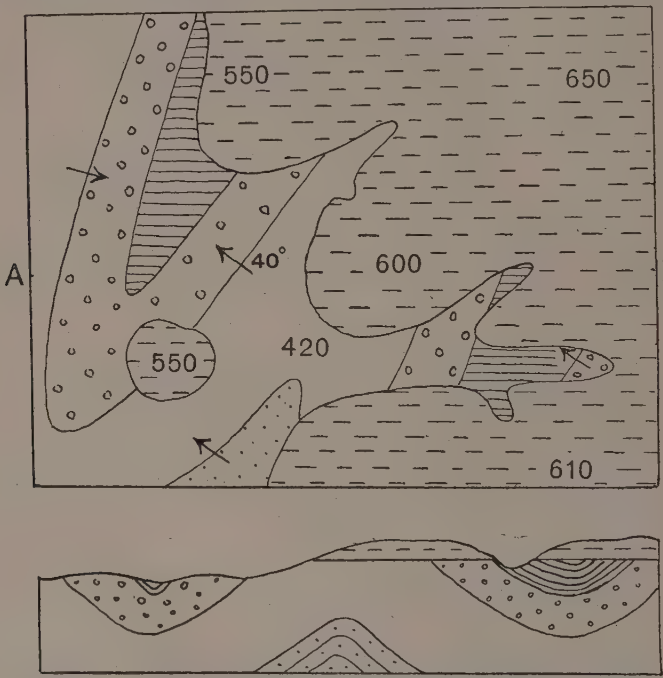


FIG. 94. Geological Map to show Unconformity. Horizontal rocks resting on denuded pitching folds. The section below is from A to B.

the upper beds were formed: it is thus possible to work out a history of events in such an area. For instance, in the case shown in *Fig.* 93b, it may be said that first the limestone and shale were formed in nearly horizontal beds, that

they were then folded and faulted, and that the whole area was worn down to a smooth plane before being submerged to receive deposits of sandstone; the area has been subsequently tilted.

Another way in which an unconformity may be recognised is of particular value in enabling us to see the presence of an unconformity on a geological map. The beds above the plane of unconformity rest in different places on different rocks (*Fig*. 94). They may thus partly conceal the structures in the older rocks, and in interpreting maps containing unconformities it must be remembered that the older rocks may show a much more complicated structure than the newer. It is often useful to draw the newer rocks on a section first, and then to fill in the structures underneath them.

Over small areas, planes of unconformity are often fairly smooth and simple, but sometimes they are quite irregular. A smooth plane of unconformity frequently represents a wave-cut platform which has been submerged and has received deposits, while an irregular unconformity may result from the burial of a land surface with hills and valleys under a mass of new sediment. Where the plane of unconformity was not quite level at the time of burial, each bed in the overlying deposits tends to extend a little further than the previous bed; this gives rise to *overlap*. In *Fig*. 93c bed C rests conformably on the bed immediately older than itself (B), but rests unconformably on the older group (A) where it overlaps.

In discussing unconformity the relations of solid rocks only have been mentioned; it may be noticed, however, that many superficial deposits (boulder clay, alluvium, peat) are unconformable to the solid rocks beneath them.

Inliers and Outliers. In solving geological maps the student will frequently meet both inliers and outliers. An *inlier* is an area of older rock surrounded on all sides by newer; an *outlier* appears on the map as an area of newer rock surrounded by older. Outliers are produced by denudation in horizontal and gently dipping strata (when they usually occur on hilltops as in *Fig*. 76); they often occur in synclines and may also be bounded by faults. Inliers

are sometimes found in valleys cut in gently dipping strata, and are often found in anticlinal areas and may be bounded by faults. Inliers and outliers are often very important because they afford an opportunity to examine a group of rocks in areas far away from those where they are widely exposed.

SUGGESTIONS FOR PRACTICAL WORK

Map work should be continued as for Chapter VIII, but it may be urged that students should spend a considerable time on work bearing on that chapter before turning to the more difficult structures dealt with here. The matter of the present chapter should be introduced in stages. At an early stage maps could be made from the block diagrams given, and further exercises worked on the outline maps in the chapter; later, students should be able to deal with folds, faults and unconformities on many Geological Survey maps. Most of the material of the present chapter can only be taught in connection with practical work on graded map exercises.

QUESTIONS

1. How would you identify a pitching fold on a geological map and in the field?
2. By means of diagrams show the appearance of (a) a dip fault and (b) a strike fault, both in plan and in section. (C.W.B.Hr., 1935.)
3. Explain, with diagram maps and sections drawn across them, the various ways in which inliers and outliers may be produced.
4. What is meant by unconformity? What series of changes may account for this structure? If possible, describe an example with which you are familiar. (C.W.B.Hr., 1935.)
5. Give diagrams to show the various structures which you would expect to find in a series of sedimentary rocks which has undergone compression.

CHAPTER X

IGNEOUS AND METAMORPHIC ROCKS

Granite. The characters of granite have already been described briefly in Chapter I. It is a crystalline rock consisting mainly of quartz, felspar and mica. Different granites vary in colour according to the slightly differing proportions of these constituents and according to the colour of the felspars, which may be pink, white or greyish (or two of these colours may be present in the one rock). In some cases the felspar crystals are of two sizes, the larger crystals having straight edges and regular form (*e.g.* on the right of *Fig.* 5). Usually the quartz is very irregular in shape and fills up spaces between other minerals; it is thus probable that quartz was generally the last mineral to crystallise in the consolidation of the granite.

A *graphic granite* is a variety consisting almost wholly of quartz and felspar and exhibiting a curious pattern resembling Hebrew lettering; the pattern is due to the intergrowth of the crystals of felspar and quartz, which must in this case have crystallised simultaneously.

Granite occurs in large masses (often forming moorlands) generally in areas which have undergone intense folding; there are great masses of granite in Devon and Cornwall (Dartmoor and Land's End), in Westmorland (Shap Fell), in North Wales (in the Lleyn Peninsula), in south-west Scotland (Galloway) and in the Highlands (near Aberdeen, Peterhead and other places). These masses vary in plan; they are often roughly circular, and the structures of the surrounding rocks are cut off sharply at the granite margin. So far as they have been explored downwards, many granite masses seem to get wider as they are traced to greater depths. Thus they have none of the structural

patterns found in the sedimentary rocks. The granite appears to have forced its way upwards into the rocks surrounding it. It is therefore called an *intrusive rock*. It was forced upwards while still molten, and it consolidated slowly in its present position; the mass did not then reach the surface, and was probably covered by a considerable thickness of rocks like those which now surround it, these having been removed since by denudation.

The molten material which crystallised to form the granite is known as *magma:* this had much the same characters as the lava poured out from a volcano, but the term lava is limited to material which reaches the surface and to the rocks formed from its cooling. In view of its mode of origin, it need hardly be said that a granite contains no fossils, and shows no signs of stratification; a granite is cut by joints, however, partly due to its contraction on cooling, and these sometimes suggest an appearance of bedding. Weathered crags (or "tors") of jointed granite often look like ruined walls, and the granite is then said to possess *mural* jointing (*Fig.* 2).

A mass of granite with the form described is often known as a *boss*. Around many bosses the rocks have been altered (metamorphosed) for a distance of a mile or more by the heat and gases given off from the hot intrusion: the rocks nearest the granite show the greatest degree of metamorphism, new minerals being formed in them, while further from the intrusion the development of spots is sometimes the chief sign of change. This belt of altered rocks, known as a *metamorphic aureole,* shows very convincing evidence of the high temperature at which the magma was intruded.

Other Coarsely Crystalline Igneous Rocks. Other igneous rocks consist of crystals of a size approximately similar to those met with in granite, but contain different minerals. These rocks are syenite, diorite and gabbro.

Syenite closely resembles granite in many ways; it is generally rather darker in colour, often reddish; it usually contains little or no quartz but much felspar, together with hornblende or augite and some biotite. There are syenites

in Carnarvonshire, in the north-west Highlands, and in the Channel Isles.

Diorites generally consist of rather smaller grains than most granites and are darker in colour: they are often grey or speckled white and green. Quartz is often lacking, although some diorites contain a fair quantity; felspar (plagioclase) is abundant, together with hornblende and often biotite. Diorites are fairly common in the igneous masses of the Southern Uplands and the Highlands.

Gabbros are still darker in colour, for they contain a much higher proportion of dark minerals than granites or syenites. Felspars are abundant, plagioclase being predominant; augite is also common, and olivine is frequently present. They occur in the Lizard area of Cornwall, in Carrock Fell (Lake District), at St. David's Head in Pembrokeshire, and in many parts of Scotland (*e.g.* in Ayrshire, the Isle of Skye and in Aberdeenshire).

It is not always easy to recognise the various types of igneous rock, and microscopic examination is often necessary before they can be properly identified. Nevertheless the varieties named here can be separated fairly well after some time has been spent in the examination of specimens; an attempt should always be made by using a lens to pick out and identify the different minerals seen in them and to estimate their proportions.

Chemical Composition of Igneous Rocks. It will be noticed that apart from quartz, which is pure silica, all the minerals which have been named in the above rocks are silicates, each containing a considerable proportion of silica combined with other oxides, such as soda, potash, alumina and the oxides of magnesium and iron. The total proportion of silica in a granite may be as much as 70 to 80 per cent.: in a gabbro it is often under 50 per cent., while syenite and diorite contain intermediate amounts. Clearly, those oxides (mentioned above) which combine with the silica to form felspar and the other silicates must make up a far higher proportion of the gabbros than of the granites. The oxides named are known chemically as bases (a base is able to react with an acid to form a salt; these particular bases

combine with silica, which may be regarded as the *acid* part of the silicates). A rock rich in these bases is known as a basic rock, of which gabbro is an example. Granite is an *acid* rock; it contains much silica. Acid rocks are those containing more than 66 per cent. of silica, basic rocks those with less than 52 per cent., and *intermediate* rocks those with silica content between these two values: syenite and diorite are intermediate rocks.

Gabbro has been formed by the consolidation of an intruded magma of basic composition, granite by the consolidation of an acid magma. In the case of an acid magma so much silica was present that there was sufficient to combine with all the bases present and to leave some over: the excess silica crystallised as quartz.

Basic rocks contain a greater proportion of heavy minerals than acid rocks, and gabbro has a noticeably higher specific gravity than granite.

Minor Intrusions. The rocks mentioned above occur in large masses, many of which are some miles across. There are other intrusions of much smaller size, which occur in two chief forms, known as dykes and sills.

A *dyke* is a wall-like intrusion, formed by the injection of magma into a fissure. Most dykes are nearly vertical, with roughly parallel walls, and they keep fairly uniform widths for considerable distances. A dyke may be from a few inches to 100 feet or more in width, and may be traceable across the country for many miles. Since a dyke is often vertical, its outcrop is nearly straight (see p. 134). Dykes may be intruded into igneous or sedimentary rocks; in the latter case they always cut across the strata. The rocks bordering a dyke are often metamorphosed, but only for a short distance from the intrusion. Many dykes are much harder than the surrounding rocks, and tend to stand out as walls, but others weather more rapidly than the surrounding country, and give rise to trenches (*Fig.* 95a).

Dykes often occur in groups or swarms, running parallel to one another. There are vast numbers in the west of Scotland, many of them intruded during the same period. The formation (and filling) of so many cracks can only mean

that the region was actually stretched or extended at that time.

A *sill* is an intruded sheet which differs from a dyke in following to a considerable extent the stratification of the rocks into which it has been injected. A sill may follow one bedding plane for a long distance, or it may pass from one bedding plane to another: it is then called a *transgressive sill*. Sills vary greatly in size: the Great Whin Sill which occurs in north-east England extends (mostly underground) for over 1,500 square miles. Sills also metamorphose the sedimentary rocks with which they are in contact. Since a sill follows the general dip of the sedimentary rocks, its appearance on the map is much the same as that of the dip-

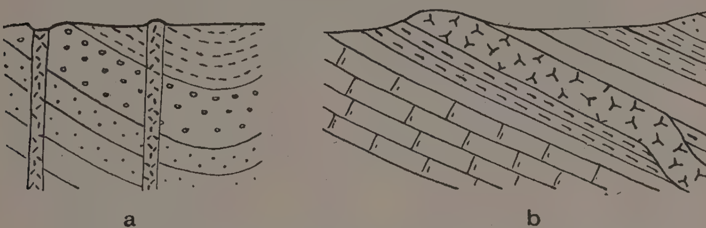


FIG. 95. Minor Intrusions. a, Dykes; b, Sill, showing transgression on the right.

ping beds, but if it is a transgressing sill it may appear at different places in the succession (*Figs*. 95b, 96).

The igneous rocks in both dykes and sills often show *columnar jointing* resulting from the contraction of the cooling mass; the polygonal columns extend from side to side of dykes and from top to bottom of sills, the joints being thus at right angles to the cooling surfaces.

It may be useful to emphasise here that all intrusive igneous rocks are younger than the rocks into which they are intruded. The age of intrusions can be fixed still more precisely when rocks newer than the intrusions are also present; in such cases they do not penetrate the newer rocks.

The Rocks of Minor Intrusions. The same kinds of magma were injected into dykes and sills as into bosses, so that rocks found in minor intrusions have the same com-

positions as granite, syenite and gabbro. They differ from those rocks, however, in the size of their crystals: the minor intrusions (on account of their size) cooled much more quickly than the larger masses, and large crystals rarely had time to form. It will be familiar that large crystals can only be grown if they are given time, and that chemical solutions which crystallise rapidly mostly yield small crystals.

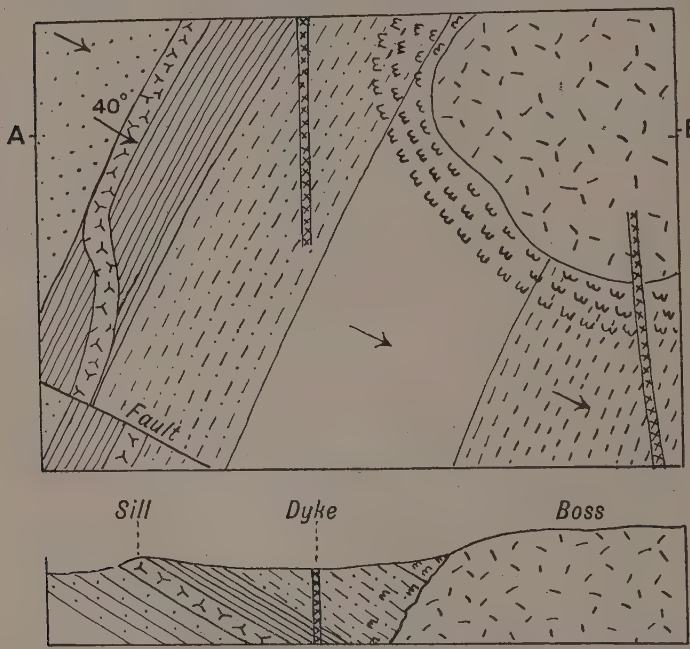


FIG. 96. Geological Map showing a Boss, with metamorphic aureole, Dykes and a transgressive Sill (the latter cut by a dip-fault). The section is from A to B.

Quartz porphyry is an acid rock found in minor intrusions. It has exactly the same composition and contains the same minerals as granite, but most of its crystals are minute, too small to identify by the naked eye. Scattered among these small crystals there are larger ones, of both

quartz and felspar (*Fig.* 97). An igneous rock with large crystals set in a mass of smaller ones is called a *porphyritic* rock; quartz porphyry is an outstanding example, but other rocks, including granite, may also be porphyritic. The formation of the larger crystals in the quartz porphyry probably began before the intrusion of the magma into the sill or dyke, at a time when the magma was cooling slowly; the smaller crystals formed more quickly when the magma was more suddenly chilled on intrusion.

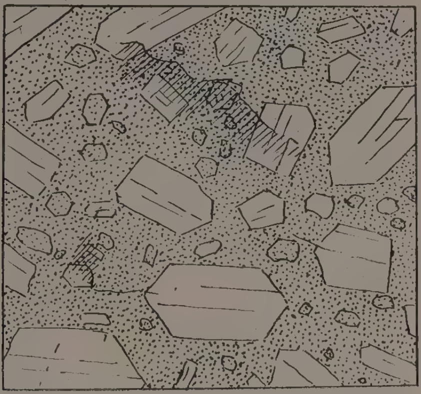


FIG. 97. Quartz porphyry, Arran. Natural size.

Dolerite is a basic rock found in minor intrusions. It has the same composition and contains the same materials as gabbro, but its crystals are small, often only just discernible by the naked eye. It is usually dark in colour, and forms a compact rock.

The Classification of Igneous Rocks. Igneous rocks, as we have already noticed, may be divided into 1, *Extrusive* (or Volcanic), and 2, *Intrusive*, the latter being again divided into (a) those coarsely crystalline rocks, which are found in large masses (known as the *Abyssal* or *Plutonic* rocks, from *Pluto*, God of the lower regions), and (b) those more finely crystalline rocks which are found in minor intrusions (known as the *Hypabyssal* rocks, meaning not quite

abyssal). Just as the Hypabyssal rocks differ from the Plutonic rocks by being more finely crystalline, so do the Volcanic rocks in general differ from the Hypabyssal rocks. For the Volcanic rocks on the whole solidified even more rapidly, in contact with air or sea, than those in the minor intrusions, and they are still more minutely crystalline; in some cases there was not time for crystals to develop at all, and the rapidly chilled lava formed a *glass*.

Besides this grouping of the igneous rocks, dependent on the size of the crystals, they can also be divided, as we have seen, in accordance with their chemical composition, into Acid, Intermediate and Basic. As each group (Plutonic, Hypabyssal and Volcanic) can be so divided, nine main subdivisions can be established. Many other factors must be taken into consideration in making a complete classification of the igneous rocks, but for the present purpose the scheme outlined is sufficient. The main groups may be summarised as follows:—

	Acid	*Intermediate*		*Basic*
Plutonic	Granite	Syenite	Diorite	Gabbro
Hypabyssal	Quartz Porphyry			Dolerite
Volcanic	Rhyolite	Trachyte	Andesite	Basalt

Mention may be made here of the *Ultra-basic* rocks, which contain no quartz and little or no felspar. The only rock belonging to this class which needs to be referred to is *Serpentine,* which consists mainly of the mineral serpentine, formed by the alteration of a rock which consisted chiefly of olivine and augite. It is convenient to defer the consideration of volcanic rocks until something has been said about volcanoes.

Volcanoes. The old description of a volcano as a "burning mountain" is inaccurate first of all because mostly there is nothing burning in the ordinary sense at all, and secondly because volcanoes are not necessarily mountains, and some are under the sea. A *volcano* may be defined as an opening through which lava, gases and other materials are extruded continuously or at intervals: around

most such openings a mountain or hill may be built up from the material ejected from the volcano.

The volcanoes best known to us from pictures are more or less conical hills, with a depression at the top known as the *crater,* from which regularly or occasionally there rise clouds of steam or other gases; the under side of the clouds may glow from time to time with the reflection of hot lava in the crater and so give the impression of burning.

The material thrown out from volcanoes includes gases (a large quantity of steam, various sulphur compounds, carbon dioxide), liquids (lava and water) and solids. The *lava* may vary in composition, being acid, intermediate or basic; basic lava is much more fluid than acid lava and flows comparatively quickly, spreading out into fairly even sheets, while acid lava is very much more viscous. Lavas are often filled with gas bubbles which become elongated in the direction of flow of the lava; a consolidated lava retains these cavities or vesicles and is called a *vesicular lava.* The surface of the lava flow is often very irregular and broken, for the upper surface may become hard while the interior remains quite molten, so that the mass continues to flow. The shape of a lava flow depends on the supply of lava and on the form of the land (or sea floor) over which it passes.

The solid material ejected from volcanoes consists mainly of fragments of lava which consolidated before ejection or during their passage through the air. It includes pieces of solidified "froth" or highly vesicular lava, known as *pumice,* more or less rounded masses of lava known as *bombs,* together with fragments of varying sizes and much fine dust. The dust is spoken of as *ash;* it must be borne in mind that this term was introduced when a volcano was thought to be a "burning mountain," but it is not "ash" in any sense. It consists of fine particles produced by an explosion blowing into the air a mass of molten lava. Particles of ash, owing to their lightness, may be carried over very wide areas; they may eventually fall hundreds of miles from the volcano (contributing, for instance, to deep sea deposits).

There are many kinds of volcano. Some only give rise to a single eruption and are not known to break out again (Monte Nuovo, near Naples); some erupt violently and do enormous damage but only at long intervals (Vesuvius, Etna, Krakatoa); others have frequent and regular eruptions of much milder type (Stromboli).

The history of Vesuvius is illustrated in *Fig.* 98. For long before 79 A.D. it had been quiet, and no memory of an outburst seems to have existed. In that year, after a series of earthquakes, an explosion blew away a great part of the crater walls and caused the destruction of Pompeii and Herculaneum, which were buried under debris, almost all of fragmentary material. The cone since formed has been built up on the side of the old crater, and has been active at intervals up to recent years, pouring out streams of lava as well as of ashes and dust.

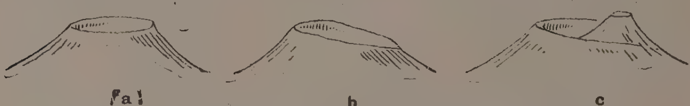


FIG. 98. Diagram to show changes in the form of Vesuvius. a, probable form before A.D. 79; b, immediately after; c, recent form.

Krakatoa, between Java and Sumatra, has a somewhat similar history. It became active in 1883 after being quiet for two hundred years: here also earthquakes preceded the great outbreak, in which great explosions blew away two-thirds of the island, leaving a hollow, in places, 1,000 feet deep. As in most such explosive eruptions, vast quantities of solid material were ejected, and dust from Krakatoa remained in the atmosphere for several years, giving rise to brilliant sunsets all round the world.

The form of a volcanic cone depends very much on the history of the particular volcano and on the nature of the material ejected. Many cones consist mainly of ash and solid debris; since most of the fragments tend to fall near the crater walls, the successive piles of material are thickest there and thin away on every side, so that such cones tend to have steep or even concave slopes (*Fig.* 99). Cones built

up by lava flows on the other hand may have more convex slopes; in the case of acid lavas (as in the Puys of the Auvergne) the cones are high in relation to their areas, but cones of more fluid basic lava (such as those of the Hawaiian volcanoes) are much flatter and do not show steep slopes. Many volcanic cones consist both of volcanic lava and ash. Associated with the deeper parts of many cones are sills and other intrusions formed by magma which did not reach the surface. It may be noted here that many volcanic islands began as cones on the sea floor which have gradually been built up above sea level.

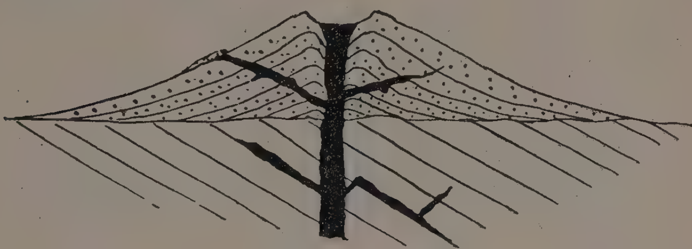


FIG. 99. Diagram section through a volcanic cone composed mainly of fragmental material; neck filled with lava with intrusions at lower levels.

The active volcanoes are distributed in belts, some of which extend parallel to the borders of the continents: an almost complete ring round the Pacific is known as the "Pacific ring of fire"; volcanoes are much less abundant around the Atlantic.

Dormant and Decaying Volcanoes. Dormant volcanoes are those which have had no eruptions during historic times but which still show fairly fresh signs of activity and have obviously been active in geologically recent times. Other volcanoes which were formerly active are declining in activity, some of them emitting only steam and other gases. *Geysers* are characteristic of some regions of declining volcanic activity. The geysers of Iceland, the Yellowstone Park (U.S.A.) and New Zealand are characteristic. Where the hot waters bring up solid particles they may form *mud-*

volcanoes (as in Sicily and in Iceland); it may be mentioned that there are other types of mud-volcanoes, however, which are not connected with volcanic activity.

Ancient Volcanoes. In past geological times there has been from time to time very pronounced volcanic activity, sometimes on a scale much greater than anything seen at the present day, in many regions where no volcanoes now exist. In Britain, for example, volcanic outbursts have characterised several distinct episodes in the geological history, but as the last occasion was many million years ago these ancient volcanoes are not represented by craters or cones in any way resembling those of active or dormant volcanoes. Their presence is inferred partly from the volcanic rocks which result from the material ejected and partly

FIG. 100. Basalt Lava Flow, Isle of Staffa. The lower part shows columnar jointing.

from old volcanic necks filled with consolidated lava or other material.

The *lava flows* of ancient volcanoes are found among the rocks in several areas, including North Wales, the Lake District, the Scottish Lowlands, the Inner Hebrides and Antrim. Because of their hardness they often stand out as hills or mountain ridges; mostly they are escarpments in which the highest peaks do not necessarily mark the sites of the old volcanic vents. Some of these lavas may indeed have resulted from lava flowing up great fissures, with no localised vents, no explosive eruption, and consequently no ejection of fragmentary material; the basalts of the Giant's Causeway and of Staffa (*Fig.* 100) probably represent such widespread flows.

In their general arrangements, ancient lava flows are interbedded with sedimentary rocks, including some of marine origin: the volcanoes in many cases must have been sub-marine. The lava sheets now have the same dip as the sedimentary rocks above and below them, and they are folded and faulted with those rocks. Lava flows thus have somewhat the same structural relations as sills, and it is not always easy to distinguish them. A sill may readily be distinguished from a lava when it is transgressive, for a lava does not change its horizon; a sill, moreover, metamorphoses the beds above and a lava does not (since, of course, they were not present when it cooled). Besides lavas, many consolidated ashes and other volcanic rocks of fragmental character occur among the deposits formed during those periods.

Volcanic necks are especially abundant in the Scottish Lowlands. They are more or less circular in plan, and generally stand out as sharp and rather unusual hills. Probably they represent the pipes which fed volcanoes, but the cones and craters have long been worn away and the pipe has been worn down, often to a great distance below its original outlet. North Berwick Law, Haddingtonshire, and the Dumbarton Castle rock are old necks of lava; the Rocher Saint Michel, Auvergne (*Fig.* 101), is a neck of agglomerate (see below).

Volcanic Rocks. The chief types of volcanic rocks may now be briefly noticed. Four types of consolidated lava have already been named (p. 162).

Rhyolite is an acid lava, the volcanic equivalent of a granite, and is whitish or pink. There are usually large crystals of both quartz and felspar, but much of the rock is very minutely crystalline. Many rhyolites show lines of flow, and nodular structure, well seen on weathered surfaces, is common. *Obsidian* may be regarded as a variety of rhyolite, consisting almost entirely of glass: it breaks with a very definite conchoidal fracture, and is much like dark bottle-glass.

Trachyte is a finely crystalline rock usually light grey in colour with the crystals arranged parallel to one another,

having streamed out in lines during the flow of the lava. It may be porphyritic. *Andesite* is similar, but is darker.

Basalt is more easily recognised and is more important to the student than the last two types. It is a dark fine-grained rock, often nearly black, having the same mineral composition as a gabbro. Basalts frequently show columnar jointing (*Fig.* 100), but this is not present in all flows.

It may be noted that when intrusive rocks occur in small dykes where they cooled very quickly they may be so fine-grained that they are practically indistinguishable from lavas.

FIG. 101. Volcanic Necks, Rocher St. Michel, Auvergne.

As already noticed, many lava flows are vesicular, especially in the upper portion. The almond-shaped vesicles (due to the pulling out of bubbles during the flow) are often filled by subsequently deposited minerals: such a lava may show patches of a light coloured mineral in a fine ground-mass, and is known as an *amygdaloidal* rock (from the Greek, *amygdale,* an almond).

Other rocks of volcanic origin are made up of the solid fragments ejected from volcanoes. A *tuff* is a consolidated volcanic ash. A tuff may have been formed as a sediment in water, and occasionally contains fossils (as on the summit of Snowdon). An *agglomerate* is a fragmental volcanic rock of coarser type: it contains angular fragments of lava which may have formed part of a temporary crust over the

crater which was later broken up by an explosion. An agglomerate is thus somewhat like a breccia: it is occasionally found filling a volcanic neck.

Metamorphic Rocks. Metamorphic rocks are those produced by the alteration of either sedimentary or igneous rocks. They may be produced by either heat (thermal metamorphism) or pressure (dynamic metamorphism), or by both combined. The formation of a metamorphic aureole around a boss and of belts of altered rock at the margin of other intrusions, has already been mentioned: these are instances of metamorphism resulting from heat. In other cases intense pressure has produced an alteration of the rocks; where the high pressure has been due to depth of burial the effects of a rise in temperature must also be borne in mind, since there is a steady increase of temperature with increasing depth. Metamorphism generally involves the recrystallisation of part or whole of the rock, but usually there is no change in the total chemical composition of the rock: the metamorphism in such cases is a kind of re-cooking of the material without either great loss or substantial addition. The rock often takes on new structures, and many of the old structures are obliterated.

Marble affords a simple example of a metamorphic rock; it is a metamorphosed limestone in which the calcite has re-crystallised in even-grained crystals, destroying any fossils which may have been present, as in the famous white marble of Carrara (Italy). It may be noticed that many limestones which are capable of taking a polish are known commercially as "marbles," although they are quite unmetamorphosed. The metamorphism of a sandstone may produce a *quartzite*, although not all quartzites are of metamorphic origin (see p. 114).

The most important metamorphic rocks are *gneiss* and *schist*. Both occur over wide areas in the Highlands and also in Anglesey and the Lizard area of Cornwall. They represent rocks which have suffered intense pressure accompanied usually by high temperatures, but the histories of the various types of gneiss and schist are too complicated to be traced here. It may be emphasised, however, that

most of these rocks have undergone such complete alteration that they show little trace of their original structure, and it is not always easy to decide whether they were formerly igneous or sedimentary.

A *schist* is a *foliated* rock, with its minerals showing discontinuous layers or folia (Latin, *folium*, a leaf). Schists will split easily along the direction of foliation, pieces breaking off rather like flakes from "puff" pastry. These often leave an uneven surface, glistening when much mica is present. Usually other crystals besides mica are visible in schists: quartz is present in many mica-schists, the mica

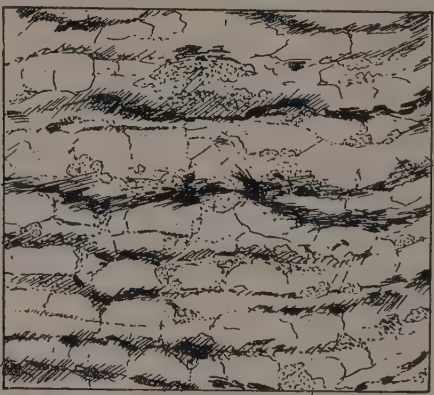


FIG. 102. Gneiss, Ross. The white mineral is Felspar; the dotted mineral quartz; black, mica. Natural size.

flakes being crumpled and moulded round the quartz grains, showing something of the intense compression which the rock has undergone. Many mica schists have been formed from argillaceous rocks; some hornblende schists are metamorphosed basic lavas.

A *gneiss* is usually a coarse-grained crystalline rock, something like a plutonic rock in grain size, but with a more or less distinct banded structure caused by the distribution of the dark and light minerals (*Fig.* 102). Many gneisses consist mainly of quartz, felspar and mica, and it is probable

that some have been formed by the metamorphism of granites: garnet and other minerals (characteristic of metamorphic rocks) are often present also.

Slate may be treated here as a rock which has suffered a change in structure owing to pressure, though it is not metamorphosed to anything like the extent of gneiss or schist. A slate is an argillaceous sediment in which a new set of cleavage planes (known as *slatey cleavage*) has been produced by intense pressure. The cleavage planes only rarely coincide with the original bedding or lamination, and

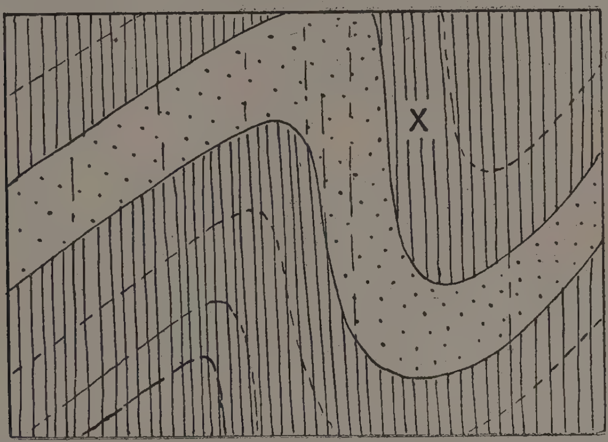


FIG. 103. Diagram to show the relation of Slatey Cleavage to bedding in clay with a sandstone band. At X the cleavage coincides with the bedding.

they may cut across the stratification in any direction: in thick masses of slate the cleavage may easily be mistaken for lamination and the real bedding may be difficult to determine. It may be indicated by the original colour bands or by beds of sandstone (in which cleavage is less marked). The cleavage planes are developed at right angles to the direction of the pressure causing them owing to the tendency of the clay particles to re-arrange themselves with the flakes in that direction under the influence of the pressure. On cleavage faces of slates, fossils are only found in those places

where the cleavage coincides with the bedding (X in *Fig.* 103). Even there the fossils are often distorted and squeezed out of their original shape.

Slates occur in many parts of Britain, generally in the older rocks, many of which have been subjected to the greatest pressures. Some of the finest roofing slates occur in North Wales. Slatey cleavage is also sometimes developed in volcanic ash.

SUGGESTIONS FOR PRACTICAL WORK

The examination and testing of rock samples as suggested in the Chapter (breaking, sorting out minerals). Determination of specific gravity of acid and basic rocks.

Map work, along the lines suggested in the last Chapter.

QUESTIONS

1. How would you distinguish basalt from andesite and granite from gabbro? Mention localities where some of these rocks may be found. What mode of occurrence would you expect each of these rocks to have? (C.W.B., 1933.)
2. Describe carefully the following rock types:—gabbro, rhyolite, basalt; and account for any differences in composition and texture? (C.W.B.Hr., 1935.)
3. An outcrop of an igneous rock has been found. What investigations would you make in order to determine the form and nature of the rock mass?
4. State the characters and composition of gneiss, syenite, pumice, quartz porphyry and gabbro. (C.W.B.Hr., 1933.)
5. Trace the history of a slate from its origin as a sediment, and mention where slates occur in Wales. (C.W.B.Hr., 1934.)
6. Describe the forms of volcanoes of different types. Illustrate your answer by diagrams.
7. Explain the principles upon which igneous rocks are classified. (C.W.B.Hr., 1933.)
8. Name the rocks in which each of the following minerals commonly occurs:—quartz, felspar, calcite, olivine, augite.
9. Draw an outline map, with a section to correspond, to illustrate a series of sandstones and shales with dolerite sills, folded into an asymmetrical syncline, and covered unconformably by a series of limestones with overlying clays, which are affected by a reversed fault. (C.W.B.Hr., 1933.)

CHAPTER XI

FOSSILS, THEIR OCCURRENCE AND USES

A fossil was defined in Chapter I as an object obtained from the ground, which either had formed a part of some organism or had some relationship with an organism. The student may be warned that peculiarly shaped or marked bodies which are obtained from the rocks sometimes have a resemblance to organisms although they have had no connection with any animal or plant. The delicate "*dendritic*" markings formed by oxide of manganese may easily be mistaken for sprigs of moss or fine seaweeds, though they are of inorganic origin. Mention has already been made of the queer shapes assumed by concretions, and some of them may be supposed (with a little imagination) to resemble various animals; irregularly-shaped flints often have been mistaken for fossils in this way. There is more excuse for regarding some of these forms as fossils than for supposing that live frogs or other animals found in pits or quarries represent ancient creatures, even though it does appear to the finder that they were really enclosed in the rock: it cannot be emphasised too strongly that fossils, whatever their structure or preservation may be, are always dead!

The Preservation of Fossils. Occasionally a fossil consists of the actual dead body of an animal. An example is afforded by the insects which are perfectly and completely preserved in *amber* (a fossil resin which trickled down a tree trunk and enclosed them).

More usually, however, a fossil consists only of the skeleton or even of part of the skeleton. We therefore know very little of the soft fleshy parts of most extinct creatures, except what can be gained by comparison of their skeletons with those of forms living to-day. The bones of

vertebrates, and especially their teeth, are frequently preserved. The skeletons of lowlier organisms such as shell-fish and corals, which are mostly formed of calcium carbonate, are also abundant. In some of these cases the actual skeleton may be found quite unchanged in the rocks. In other cases the material of the original skeleton has been replaced by a different substance, so that while retaining much detail of the structure no part of the original substance remains: the preservation in cherts of skeletons which formerly consisted of calcium carbonate (referred to on p. 123) illustrates this; not infrequently calcareous skeletons are represented by fossils made of silica or of iron pyrites, while tree trunks may also be replaced by calcite or silica.

In some cases again the fossil is a mere *mould*, a hollow in the rock where a skeleton has been, showing its shape and the pattern of its markings. This has occurred for example where a shell has been buried in a deposit of sandstone, which became consolidated around it before percolating water removed all trace of the shell and left a hollow. Sometimes, too, the mud which filled a hollow shell preserves an internal mould after the shell has disappeared. Such fossils, though incomplete, are often very valuable and may give as much information as the complete shell itself.

Other records of animal life are represented by the footprints made by land animals on sand or mud, the tracks made by crawling worms and the burrows of worms or shell-fish.

Geological Age. The most important use of fossils is in connection with the geological age of rocks, and the implications of this may be summarised before discussing fossils further.

The reader has become familiar with references to older and newer rocks. He knows that if he takes a journey from London to the Midlands he travels against the dip and passes from newer to older rocks, while if he continues into North Wales the rocks are older still. Quite apart from any knowledge of fossils it is thus possible to arrange rocks in order of age; by a study of the nature of the rocks themselves and of any unconformities which may occur it is

possible to get a considerable knowledge of the geological history of any area (p. 152).

But the sequence of events which is made out may only apply to that area, and another area may have a different history. How then is it possible to fit together the two accounts and to see how the events of one area were related to those of the other? The problem is almost the same as if we had a full knowledge of the histories of Britain and, shall we say, Russia, but without any dates and with no events common to the two; the discovery of records of travellers who spent some time in both countries, however, would enable us to connect the two histories at various points. The geological histories of separate areas could not be connected until it was realised that many of the same fossils occurred in them, and that these represent the remains of creatures which at one period lived in the various regions.

It was William Smith (the maker of some of the earliest geological maps) who showed that each rock group is characterised by its own assemblage of fossils, and that the rocks above and below it have different fossils. This fact enables us to *correlate* the equivalent rock groups in different areas: even when the rocks themselves are different in character, consisting, for example, mainly of sandstones in one area and mainly of limestones in another, the existence of similar fossils in these makes it clear that they are of identical age. We can go further than the mere arranging of rocks in an order of age: we can determine the characters of the organisms living in each period.

These conceptions have gradually led to the division of geological time into a number of *Eras* and *Periods:* the rocks belonging to each Period are said to constitute a *System.* The names of the systems are given below. It should be emphasised that the periods are not necessarily of equal length; their limits have been determined by the most convenient grouping of the rocks into systems: this was mainly done in Britain, and the rocks of the different systems represent the natural divisions, each system differing in fairly obvious respects from those above and below it.

The student need not immediately commit this list to memory. Frequent reference should be made to it during the reading of this chapter and the next. The position of the Carboniferous period may usefully be remembered, as representing practically the end of the Palæozoic and as preceding the Age of Reptiles: it of course includes the time when coal was formed in Britain.

Groups and Eras	*Systems*	*Vertebrate Life*
Tertiary Group Cainozoic Era = time of recent life	Pleistocene[1] Pliocene Miocene Oligocene Eocene	The Age of Mammals
Secondary Group Mesozoic Era = time of middle life	Cretaceous Jurassic Trias } New Red Sandstone	The Age of Reptiles
Primary Group Palæozoic Era = time of ancient life	Permian } New Red Sandstone Carboniferous Devonian Silurian Ordovician Cambrian	Appearance of Amphibia Appearance of Fishes
	Pre-Cambrian or Archæan	

Fossil Vertebrates and their Geological History. The vertebrates are creatures with backbones: they include the fishes, which live in water and possess fins, and the amphibia, reptiles and mammals which are normally four-footed and adapted in different degrees for life on land: the amphibia must lay their eggs in water where their early life is spent, while the reptiles lay their eggs on the land, and normally spend their life on land, as do the mammals.

[1]The Pleistocene is often regarded as the chief member of a Quaternary Group.

Fishes are thus more commonly represented as fossils than any of the other groups, for there is more chance of a skeleton being preserved if it is buried quickly in accumulating sediment. Land creatures are only occasionally carried into places where they are buried and their bones preserved.

The fossils of these various vertebrate groups do not always resemble very closely the living forms with which we are familiar. Many fossil fishes are represented by thick scales or bony plates which covered the outside of the body, for many early fishes had very few internal bones compared with such fishes as the herring. Similarly the earliest mammals were primitive creatures rather like some now living in Australia, and the horses, elephants and monkeys have only recently appeared. The faunas of the past have not merely been different from that of the present; there have been an enormous number of different faunas in the past, one succeeding another and showing changes which have become more pronounced at later times.

The progressive development of life, known as *evolution,* is illustrated very impressively by the fossil forms of many groups of animals. It is not proposed to discuss the biological and other evidences of evolution, but it is essential that the reader should realise that the study of fossils is not merely a matter of geological interest, but that it has an important bearing on biological problems. The student of biology is concerned with the survivors of long lines of descent. Fossils enable us to learn something of the earlier stages of these lines as well as of the many lines which came to an end long ago, of which there are no living representatives. Our knowledge is far from complete, first because a fossil is in most cases only a part of the organism it represents, and secondly because the fossils so far discovered probably represent only a fraction of the different types which have existed. Yet the fossils already known enable us to sketch many of the main facts in the history of life.

It is sufficient to indicate briefly the main stages in the history of the vertebrates, with reference to the table on p. 176. The chief episodes may be outlined as follows:—

1. A long period (probably longer than all the time since) during which there were no vertebrates at all.

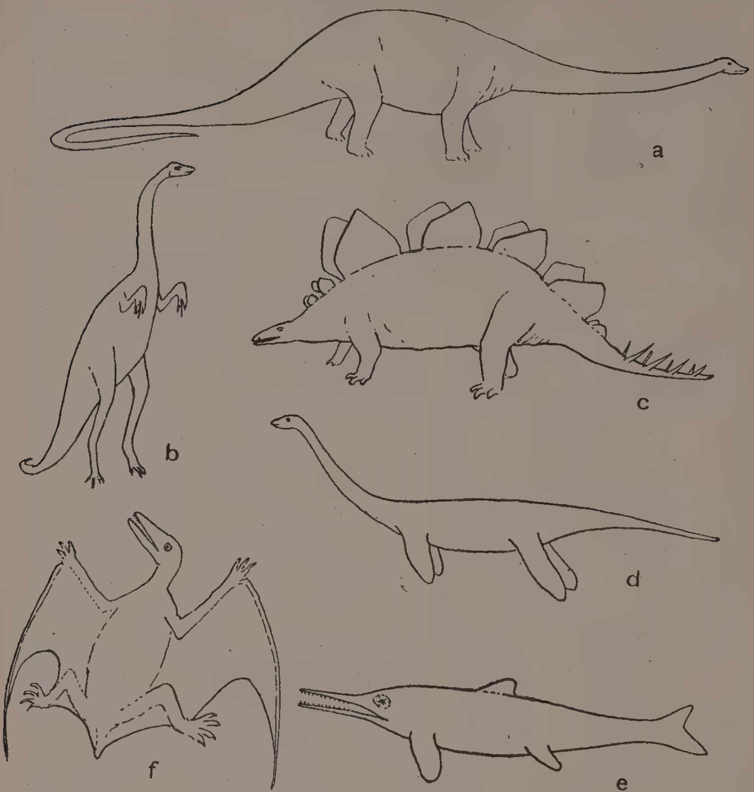


FIG. 104. Some characteristic Reptiles of the Age of Reptiles, drawn to different scales.

a, *Diplodocus,* about 80 feet long; b, *Struthiomimus,* about 13 feet high; c, *Stegosaurus,* about 25 feet long; d. *Plesiosaurus,* an aquatic reptile; about 15 feet long; e, *Ichthyosaurus,* an aquatic form about 12 feet long; f, a Pterosaur, wing expanse about 10 feet.

2. A period during which fishes of many types lived in the seas and rivers, but when there were no land creatures.

3. The appearance of amphibia in the Devonian period, probably developed from fishes by acquiring lungs and limbs. They were the only land vertebrates in the Carboniferous, except for some early reptiles.
4. The Age of Reptiles: these creatures flourished in the Permian and dominated the land throughout the Mesozoic era. They included the *Dinosaurs* (or "terrible lizards"), some of which grew to enormous size (*Fig.* 104a), while others were small, light and active (*Fig.* 104b); some were herbivorous, others carnivorous, and some developed bat-like wings (the *Pterosaurs*) and began to fly

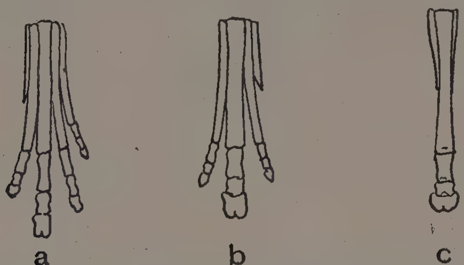


FIG. 105. Stages in the development of the foot of a horse during the Cainozoic. a, an early ancestor with four toes and trace of a fifth; b, a mid-Cainozoic form with three toes and trace of a fourth; c, a modern horse with one toe and traces of two others.

(or at least to "plane"). Other reptiles (*Ichthyosaurs*) returned to the water and became fish-like in shape (*Fig.* 104e), as the whale has done among the mammals more recently. Most of the Reptiles became extinct by the end of the Cretaceous. Birds also appeared in the Jurassic, probably as an offshoot from the Dinosaurs.
5. The Age of Mammals lasted while the Tertiary rocks were being laid down. Some mammals existed during the Mesozoic, but they were few in number. At the beginning of the Cainozoic they spread

rapidly and became fitted for different modes of life until they occupied all the places in nature where reptiles had formerly existed. During this era we can trace the gradual development of horses (*Fig.* 105), camels and elephants from simple and generally smaller forms which lacked some of the more striking characteristics by which their modern representatives are familiar to us. Innumerable fossils provide links which enable us to connect these ancient mammals with their descendants. Man did not appear until towards the end of the Age of Mammals.

Invertebrate Fossils. Fossil invertebrates are more abundant than vertebrates in every System. Many fossil invertebrates belong to groups that are not very familiar, for they are either extinct or rare now. There are many different types of invertebrates, which are conveniently divided into about 9 groups or *phyla:* it will be most suitable to take these phyla in turn, describing particularly the forms which occur commonly as fossils. The simplest phyla are dealt with first, the later ones in general representing more advanced forms; it should be noted that all these phyla were already represented in the seas at the beginning of the Palæozoic.

In the following pages reference is made chiefly to groups of fossils and only occasionally to names of individual forms. It is desirable, however, to make it clear that fossils are named according to the same Linnean system of nomenclature which is adopted for plants and animals. Each group of individuals with common distinctive characters is regarded as a *species;* groups of closely related species are called *genera* (singular, *genus*). Each species has two names, a "surname" or generic name which comes first (and which also applies to all the species in that genus), and a second or specific (species) name. There are so many thousands of species that it is rarely possible for a student beginning the study of fossils to remember the names of any but a few of those he collects for himself. Species names are not given therefore in the following notes, but

occasionally genera are mentioned or illustrated in order to represent examples of different groups. The student, however, should at first confine his attention to the names of the fossil groups; the names of phyla are given to make relationships clear, but they need not be learned immediately by those unacquainted with them.

The Protozoa. The Protozoa are simple and almost structureless animals, mostly of small size, in which the body is a single unit (or cell) of living matter. They are important geologically in so far as they secrete skeletons. The *Foraminifera* are Protozoa which make skeletons of calcium carbonate, often in the form of minutely coiled shells (*Fig.* 106a). They give rise to extensive deep-sea deposits to-day, and are found in many marine limestones of all ages, notably the Chalk. *Radiolaria* are Protozoa with skeletons of silica (*Fig.* 106e, f); they also occur in modern deep-sea deposits and in some sedimentary rocks (*e.g.* some cherts, p. 123).

Sponges. The sponges belong to the phylum Porifera, in which the body consists of a number of cells, as in all the remaining phyla. They are occasionally important as fossils, many occurring in the Cretaceous rocks. Sponges have internal skeletons which are built up of great numbers of small, regularly shaped bodies known as *spicules:* the skeletons may be calcareous, siliceous or horny (as in a bath sponge). The detached spicules are recognisable even when complete skeletons are lacking (*Fig.* 106g).

Corals. Corals are members of the great phylum *Cœlentera,* in which the animals have a simple sack-like body with a mouth at one end surrounded by tentacles; the sea anemone is a familiar member of the group (*Fig.* 107e). A sea anemone is attached to the rock but forms no skeleton of its own: a coral may be regarded as a kind of sea anemone which secretes a skeleton of calcium carbonate. The modern reef-building corals have already been mentioned (p. 87). Fossil corals include many other types, some of which formed reefs in earlier ages. Corals were very abundant in the Silurian, Carboniferous and Jurassic periods: they became rare in the Tertiary in these latitudes.

The skeletons of *Simple corals* represent single individuals. Generally the skeleton is conical or cylindrical, often with a hollow cup or calyx at one end in which the living animal was situated, depositing more calcium carbonate as it grew. Looking into the calyx of most simple corals, or at a skeleton cut across transversely at some

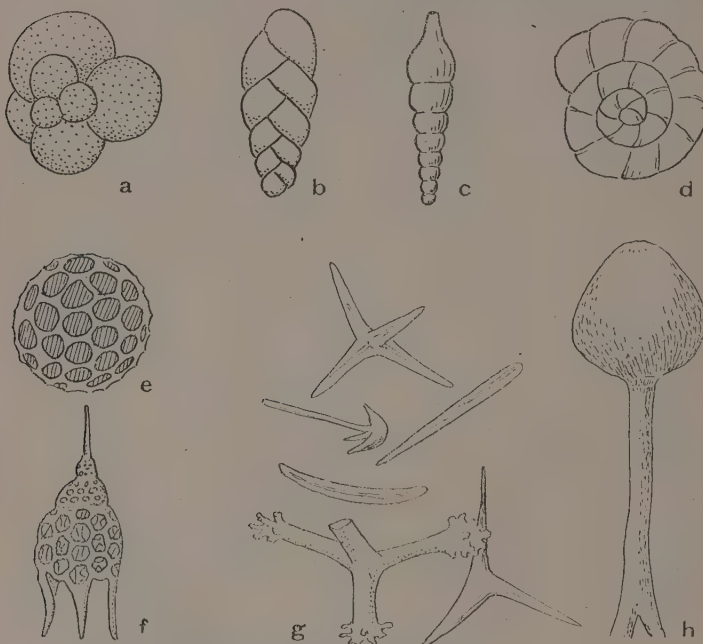


FIG. 106. a-d, Foraminifera, much enlarged (a, *Globigerina*; b, *Textularia*; c, *Nodosaria*; d, *Rotalia*); e, f, Radiolaria, much enlarged; g, sponge spicules, much enlarged; h, *Siphonia*, a Cretaceous sponge, × 1/3.

point, a number of radial plates can mostly be seen (*Fig.* 107a, b). These help in the recognition of many corals.

A Compound coral consists of a number of individuals whose skeletons are joined together. Each such colony has grown from a single individual which has formed branches.

The individuals in a colony may have skeletons which are circular in section and which are arranged like the branches of a tree (*Fig.* 107c), or they may be polygonal in section because they are packed closely together and leave no intervening spaces (*Fig.* 107d). Corals of all these types usually show the radial plates mentioned above.

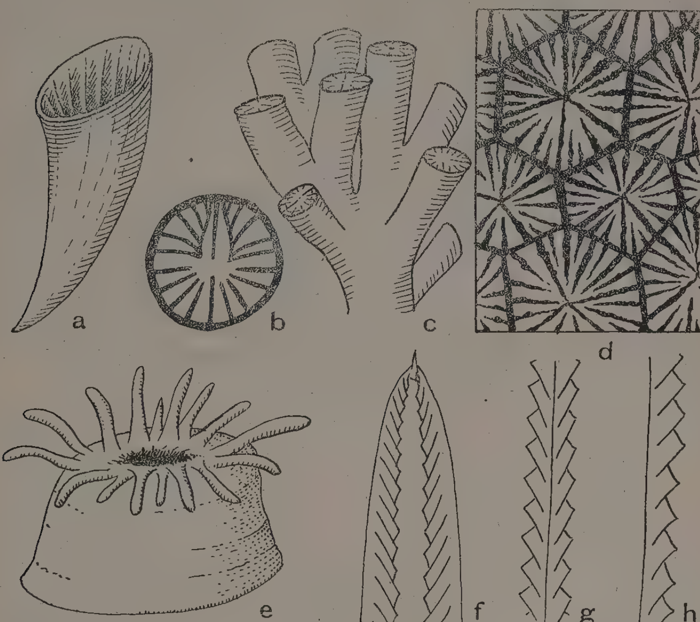


FIG. 107. Various forms of Cœlentera. a, a simple coral (*Zaphrentis*, Carboniferous); b, the same in section; c, d, compound corals (c, *Lithostrotion*, Carboniferous; d, *Isastrea*, Jurassic); e, a modern sea anemone; f-h, Graptolites (f, *Didymograptus*, Ordovician; g, *Diplograptus*, Ord.-Sil.; h, *Monograptus*, Sil.).

Graptolites (*Graptoloidea*). Graptolites were also members of the Cœlentera, but the individuals were small, each occupying a simple and delicate conical cup made of horny material. These cups were arranged in rows with a

canal connecting the cups in each row: different graptolites had different arrangements of these rows (*Fig.* 107f-h), some having two rows with a "tuning fork" pattern (*Didymograptus*), some a simple line with cups on either side (*Diplograptus*) or on one side only (*Monograptus*).

Graptolites usually are unimpressive fossils, and the details described cannot be made out except in well preserved specimens. The name "Graptolite" means "writing on stone," and many of them look at first sight like pencil markings on shale. They are very important fossils since they are confined to the lower Palæozoic rocks. They became extinct in the Silurian.

Worms. Such worms as the annelid or segmented worms, familiar in the earth worm, have no skeletons, and fossils consist only of their tracks and burrows; other worms make a simple calcareous tube, and these are met with as fossils, often attached to shells.

The Crinoids. The Crinoids belong to the phylum *Echinoderma*. They are closely related to the starfishes, which are not usually common as fossils but are well represented on our coasts to-day. A starfish has five "arms," has its mouth on the underside and creeps about in search of food. A typical crinoid may be described simply as like a starfish turned upside down with its mouth uppermost, and surrounded by more numerous arms which act as collectors of minute food particles, the animal being attached by a stem to the sea floor. The organism looks almost plant-like, and is popularly called a *sea-lily* (*Fig.* 108a).

Its skeleton consists of calcareous plates; those of the stem have already been described (*Fig.* 67a). The body portion has thinner plates generally arranged in circles of five (a 5-rayed pattern is common in this phylum).

Crinoids were very abundant in the Palæozoic and sometimes in the Mesozoic. They are less important to-day and many of the survivors are no longer attached by a stem, but are free moving.

The Sea Urchins. The Sea Urchins or *Echinoids* are also members of the Echinoderma. Each is enclosed in a skeleton of a more or less spherical shape formed from plates

arranged in a 5-rayed pattern. The creature's mouth is on the base, and the urchin normally moves about by means of a series of suckers (tube-feet) which protrude through pores in certain of the plates (*Fig.* 108c). On the plates of the common sea urchin of the present day (*Echinus*) are small knobs which bear spines in the living creature, making it look something like a hedgehog. Some Echinoids have only a few heavy spines, in others they are hair-like.

Some of the sea urchins have modified their form by

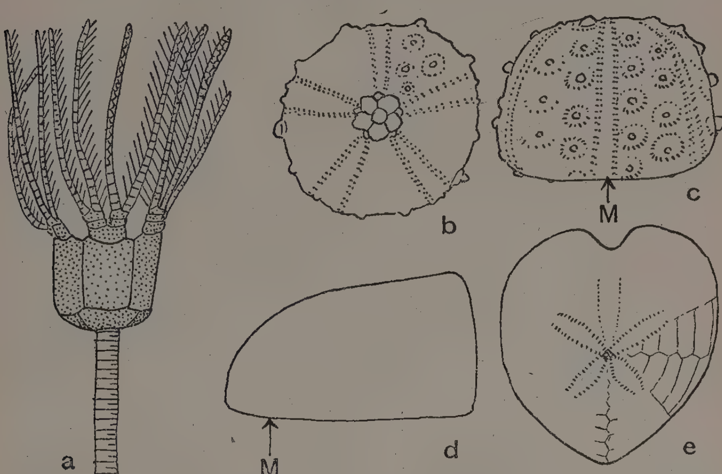


FIG. 108. Various forms of Echinoderma. a, a typical Crinoid (Carb.); b, c, a Regular Echinoid, from above and from the side (*Hemicidaris*, Jurass.); d, e, an Irregular Echinoid (Heart urchin, *Micraster*, Cret.). M, shows the position of the mouth. All slightly reduced.

becoming heart-shaped. *Micraster*, a typical Chalk fossil, is an example of these (*Fig.* 108d, e). Echinoids became abundant after the Palæozoic.

Bryozoa. The Bryozoa (literally, moss-animals) or *Polyzoa* are colonial forms in which numerous small organisms build up a connected skeleton, sometimes of calcium carbonate. They are sometimes plant-like in ap-

pearance, but vary greatly in form. Often they are attached to shells. They are fairly common fossils in many systems.

Brachiopoda. The Brachiopoda are characterised by having a shell consisting of two hinged *valves* which are unequal. The valves are symmetrical; that is, if the shell is placed so that one valve is facing the observer, a line can be drawn across it which exactly bisects it (*Fig.* 109a).

In many Brachiopods there is a hole in the apex of the larger valve: through this passed a fleshy stalk by which

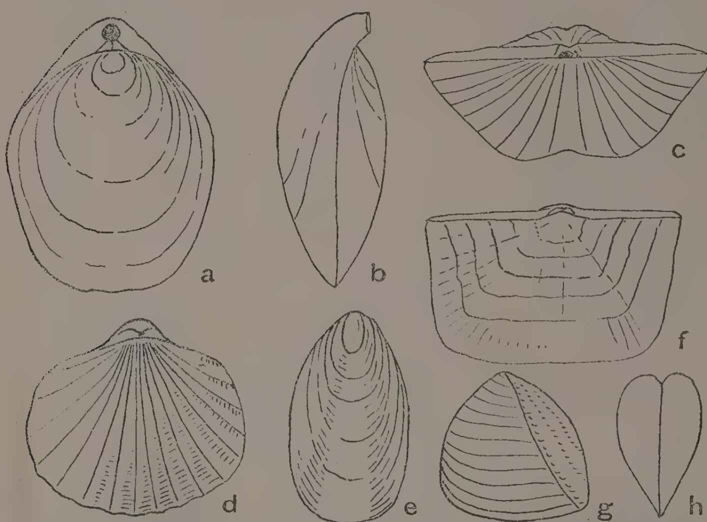


FIG. 109. Various forms of Brachiopoda (a-f) and a Lamellibranch
Carb.); d, *Rhynchonella* (Jur.-Cret.); e, *Lingula* (early Palæozoic
g, h). a, b, *Terebratula* (mainly Mesozoic); c, *Spirifer* (Dev.-
to pres.); f, *Leptæna* (chiefly Sil.); g, h, *Trigonia* (Jur.).

the organism was attached. The shells vary much in shape and ornament; *Terebratula,* when viewed from the side, looks like a Grecian lamp (*Fig.* 109b), and is known as a lamp shell, the hole referred to appearing to be the place through which the wick came; *Rhynchonella* has radiating ribs and the apex of one valve is beak-like (*Fig.* 109d);

Spirifer and other forms are extended at the hinge line (*Fig.* 109c). The above and most other genera have calcareous shells; the shell of *Lingula* (*Fig.* 109e) is more horny.

Lingula has lived unchanged from the early Palæozoic to the present day, but in the Palæozoic there was also a wide variety of other genera; *Terebratula* and *Rhynchonella* were almost the only common types in the Mesozoic. The Brachiopoda became less common in the Cainozoic, but some are still living. They are all marine.

The Lamellibranchia. The Lamellibranchia are members of the phylum *Mollusca* and must be distinguished at once from the Brachiopoda, although like them they have a skeleton of two valves hinged together (that is, they are *bivalve*). Unlike the Brachiopoda, Lamellibranchs are never symmetrical along a line crossing the valves (*Fig.* 109g), but the valves themselves are often (though not always) equal (*Fig.* 109h). Lamellibranchs are very common at present both in the sea and in fresh water. The cockle, mussel and oyster are well-known examples. Lamellibranchs have been specially common during the Cainozoic, but the group has been fairly abundant since the Palæozoic.

The Gasteropoda. Gasteropoda are also Molluscs, but they have a *univalve* shell, usually conical and coiled in a "corkscrew" spiral, as in the whelk and winkle. Most Gasteropods are marine, some fresh water and others terrestial (snails). Gasteropods have existed since the Palæozoic, modern types appearing abundantly in the Cainozoic.

Nautilus. There remains one group of the phylum Mollusca not so familiar to most of us, the *Cephalopoda*, which is less common at the present time than in the past. One survivor, the pearly *Nautilus*, illustrates the structure of the more important members. It has a univalve shell consisting of a cone coiled in a spiral which is flat, like a watch-spring, not a corkscrew (*Fig.* 110). The shell of *Nautilus* is partitioned off into some thirty air-chambers, the animal occupying only the front chamber but having a tube (*siphuncle*) extending back through the others (*Fig.* 110c). *Nautilus* lives in warm seas now, but its empty shell, supported by these chambers, is floated to many shores.

Nautilus is a very common fossil in the Jurassic. When it is found as an internal cast, with the shell itself missing, the edges of the partitions between the chambers are seen as wavy lines on the cast: these are called *sutures*. In the Palæozoic the ancestors of the Nautilus group occur; among them are long, conical, chambered shells which are straight (*Orthoceras*) or only slightly curved.

Ammonites. The Ammonites, sometimes known as "snakestones," are similar to *Nautilus* in many ways and form another division of the Cephalopoda: as in *Nautilus*, each shell is chambered and coiled in a plane spiral, but the nature of the coiling varies, and there is much variety in

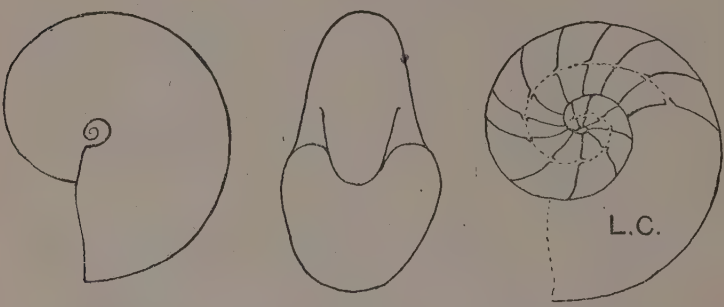


FIG. 110. The shell of *Nautilus*. a, from the side; b, from the front; c, in a median section, showing the living chamber (L.C.), the chambered shell and the course of the siphuncle. About ¼ natural size.

the shape of the shell. Moreover while a *Nautilus* shell is nearly smooth on the outside, an Ammonite may be ornamented with ridges or knobs. The sutures of Ammonites, seen on an internal cast, are often very intricate, and much more frilly than those of *Nautilus* (*Fig.* 111d).

Ammonites are among the most characteristic fossils of the Mesozoic and, in Britain, especially of the Jurassic. They became extinct at the end of the Cretaceous. Their ancestors in the Palæozoic include the *Goniatites*, which have simple wavy or angular sutures (*Fig.* 111c).

Belemnites. The Belemnites seem at first sight to be quite different from the Cephalopoda just described, for the most frequent fossil consists of a cigar-shaped solid body, popularly known as a "thunder-bolt." The usual fossil

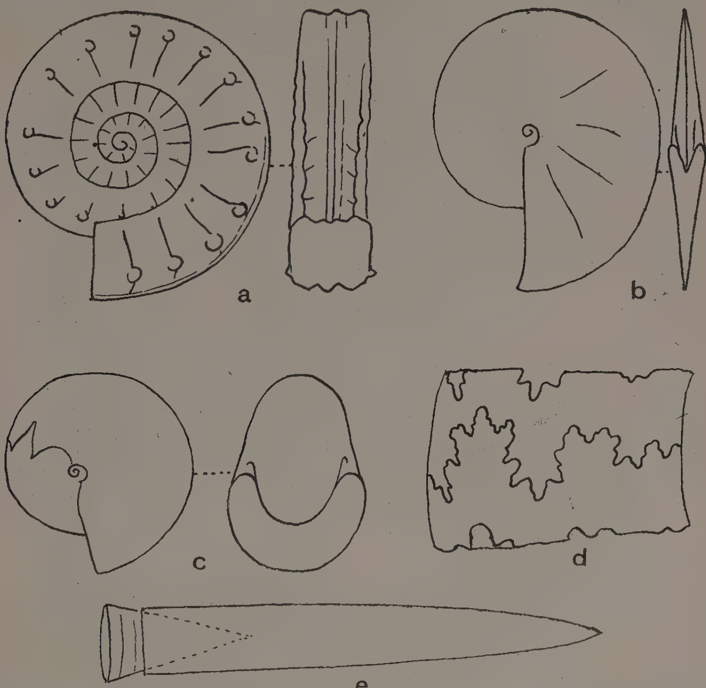


FIG. 111. Various forms of fossil Cephalopoda. a, b, Ammonites; a, a tuberculate form (*Coroniceras*), b, a thin form (*Oxynoticeras*), both from the Lias; c, a Goniatite, showing the simple suture line; d, a portion of a cast of an Ammonite showing the complicated suture line; e, a Belemnite, showing the conical chambered shell and the guard. All slightly reduced, except a, which is about 1/10 natural size.

belemnite, however, represents only the "guard" which partly surrounded a chambered conical shell of Cephalopod pattern (*Fig.* 111e). The whole skeleton in the Belemnites

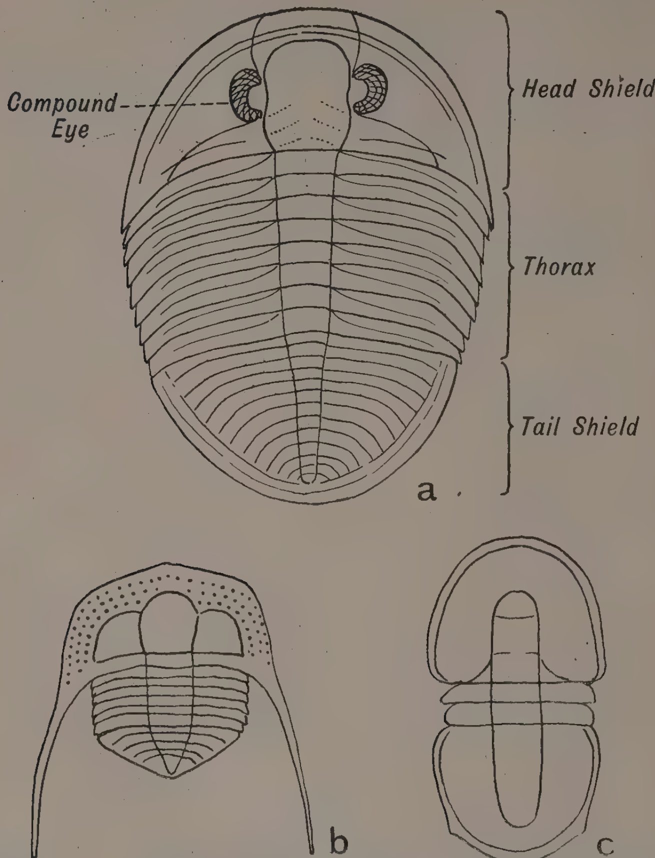


FIG. 112. Various forms of Trilobites. a, *Ogygia* (Ord.); b, *Trinucleus* (Ord.); c, *Agnostus* (Camb.). a, slightly reduced; b, natural size; c, four times natural size.

seems to have been enclosed within the animal, as in the living cuttlefish, which is closely related to the Belemnites.

Belemnites are only known from the Mesozoic rocks, and they became extinct in the Cretaceous.

The skeletons of the various groups which make up the Mollusca are very different in character, and it may appear surprising that such diverse groups are placed together in a single phylum. It may be noted that, in their soft parts, the various members of the Mollusca have many features in common; particularly important is the presence of a muscular organ known as the foot, on which a Gasteropod crawls (the word Gasteropod means " stomach-footed "), and which in a Cephalopod is modified to form the tentacles surrounding the head (Cephalopod means " head-footed "). The Brachiopods, which are placed in a separate phylum, have different internal characters.

Trilobites. Trilobites are primitive members of the *Crustacea,* a group which includes forms with a hard outer skeleton, as in crabs and lobsters; together with insects and spiders the Crustacea make up the phylum *Arthropoda* (forms with jointed limbs).

Trilobites usually have a flattened body showing a varying number of segments, resembling the annelid worms in the last character. The head-shield usually bears two large compound eyes, though some trilobites are blind. The limbs are very rarely seen for they were underneath the body, and only the upper surface is usually seen. This surface is always " trilobed " by grooves extending from the head to the tail.

Trilobites were extremely common in the early part of the Palæozoic, but became rare later and did not survive into the Mesozoic.

Fossil Plants. The geological history of the vegetable world is as interesting as that of the animals, but it may be summarised more briefly because except in a few parts of Britain the student is not likely to meet many fossil plants other than those of the Carboniferous.

In the early part of the Palæozoic there was practically no plant life except in the water: lowly sea-weeds existed and formed the food of many animals, but the land must have been bare. Land plants of simple type became important during the Devonian and Carboniferous (and it is significant that not until then did the first land animals

appear). The forests of the Carboniferous were different from those of to-day, for the great trees of that period belonged to types of plant which are now either extinct or are represented only by diminutive forms. Many were swamp-dwelling, with their roots in water: such were *Calamites* (the ancient giant representative of the modern horse-tail,

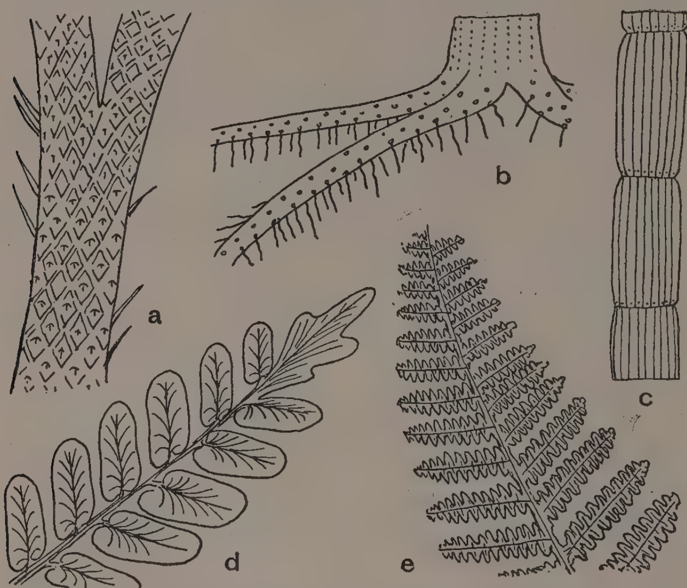


FIG. 113. Some Coal Measure Plants. a, *Lepidodendron,* stem with some leaves attached, slightly reduced; b, *Stigmaria,* the root of the last (and allied) trees, common in the bed under coals; much reduced; c, Calamite, stem, somewhat reduced; d, *Neuropteris,* a fern-like leaf; e, *Pecopteris,* a fern (natural size).

Equisetum), and *Lepidodendron* (a relative of the club moss, *Lycopodium*). Ferns (such as *Pecopteris*) were also abundant besides other plants with fern-like leaves (including *Neuropteris*), which had seeds and not spores (as do the true ferns).

Flowering plants did not appear until later, during the Mesozoic, and broad-leaved trees of modern aspect became abundant in the Cretaceous. The floras of Britain in the early Cainozoic included genera which now occur in subtropical regions, and probably our climate was warm then.

The Uses of Fossils. An indication of some of the uses of fossils has already been given. Their greatest importance is in fixing geological age and in correlating rocks in different areas. For this purpose the most important fossils are those belonging to groups which lived for a comparatively short time but which spread over wide areas during that time. The graptolites are of much use in this respect; many of them floated and they were carried for great distances. The different divisions of the Ordovician and Silurian have their own peculiar types. Graptolites, however, may be used by those not knowing any of the different kinds: they often occur in grey shales which look like the rocks of the Coal Measures, and pits have been sunk in search of coal in graptolite-bearing rocks: since these must be Silurian or older the search can at once be shown to be worthless.

Fossils are used in the search for coal and oil, and in all cases where particular beds are being sought for any purpose; if fossils characteristic of each rock group are known, it is possible to determine whether the bed which is being looked for is likely to lie below the surface at any place.

Fossils also assist in the interpretation of the conditions under which rocks were laid down. Marine types and fresh-water types show the general conditions, while corals, crinoids and many brachiopods indicate that the sea-water was clear and not muddy. The presence of animals which lived on the sea bottom (such as Trilobites) and have normal eyes shows that the water was shallow (for light does not penetrate into deep water). Thick molluscan shells may indicate shallow water, where shells must stand the buffeting of the waves. An indication of the climatic conditions may also be given by some forms, especially in later deposits by the plants.

Another important aspect of the study of fossils has already been referred to, that is, the evidence obtained from fossils as to the manner of evolution. The history of life in general is made clear by them, and in detail the actual evolution of certain types from their ancestors has been traced by collecting fossils from every bed through a thickness of rocks; some stages in the evolution of the Lamellibranch *Gryphæa* from an oyster-like shell are shown in *Fig.* 114.

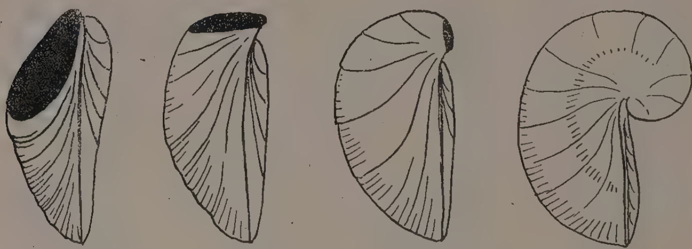


FIG. 114. Stages in the evolution of *Gryphæa* from an oyster-like shell, all from the Lias rocks. a, with a large area by which the shell was attached, here shown black; b, c, two later stages with the attached area reduced and the shell showing curvature; d, *Gryphæa* (the Devil's Toe Nail).

SUGGESTIONS FOR PRACTICAL WORK

The drawing of specimens is the most important practical work connected with this part of the course. Students should aim at making simple clear drawings of good size, to show the structures plainly, but not to attempt to make heavily shaded "pictures."

If spare specimens of ammonites or corals are available (for example, if they can be collected locally) they may be ground down to show the internal structures.

QUESTIONS

1. Why is the study of fossils of importance to the geologist? (C.W.B.Hr., 1935.)
2. Write a general account of the geological history of the Vertebrates. In what ways did Mesozoic Reptiles resemble, and in what ways did they differ from, the Tertiary mammals?

3. How would you distinguish between the shell of a Lamellibranch and that of a Brachiopod? Give drawings to show the chief types of each.
4. What are the characters by which you distinguish between Gasteropods, Ammonites, Goniatites and *Nautilus?*
5. Name and illustrate the chief types of fossils to be found in the Mesozoic (or the Cainozoic) rocks.

CHAPTER XII

THE HISTORICAL GEOLOGY OF BRITAIN

The principles on which the rocks are divided into groups and systems have been sketched in the last chapter. The reader should have a geological map of Britain by him when reading the present chapter, and he should become familiar with the broad distribution of the systems in Britain; the old rocks generally occur in the west, in Cornwall and Devon, Wales, the Lake District and Scotland, while newer rocks (Mesozoic and Cainozoic) occupy all the area south and east from the Midlands.

In this chapter the general characters of the rocks in each system are summarised, some mention is made of their distribution, of their fossils, and of how they are related structurally to the rocks around them, and an account is given of the conditions under which they were probably laid down. It must be emphasised that conclusions about these conditions have been reached mainly from a consideration of the other facts referred to.

Pre-Cambrian or Archæan Rocks. The Pre-Cambrian rocks represent a vast period of time, but they cannot conveniently be subdivided into systems because they contain practically no fossils. So that although a local sequence of events can be made out for each separate area, the various divisions of the Pre-Cambrian in the different areas cannot be correlated with any certainty. This illustrates very clearly the extent to which geologists are dependent on fossils for any systematic knowledge of earth history.

The biggest area of Pre-Cambrian rocks in Britain is in the Scottish Highlands, where north-west from a line running from Stonehaven to the Firth of Clyde Pre-Cambrian rocks predominate (*Fig.* 115). In places they are cut by in-

trusive granites of newer date, elsewhere they are overlain unconformably by small outliers of other rocks, but the greater part of the area is made up of gneisses and schists with very complex structures.

Along the extreme north-west, forming the coast of Sutherland and Ross, the highly metamorphosed gneisses are overlain by a thick group of red sandstones (the Torridon Sandstones) showing no sign of metamorphism; both groups are proved to be of Pre-Cambrian age, since Cambrian rocks rest unconformably on them; it is thus apparent that they represent two quite different stages in the Pre-Cambrian, and that the gneiss in that region underwent metamorphism long before the end of Pre-Cambrian times.

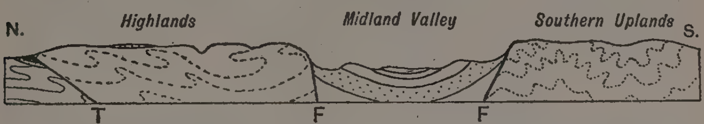


FIG. 115. Diagrammatic section through Scotland, showing the broad distribution of the major rock groups. T, thrust; F, F, faults. Pre-Cambrian rocks in the Highlands; Ordovician and Silurian in the S. Uplands; Old Red Sandstone and Carboniferous in the Midland Valley.

Apart from the Highlands, Pre-Cambrian rocks are only found in small inliers in the rest of Britain. Sometimes these show rocks with characters similar to the Pre-Cambrian rocks in Scotland: a large area in Anglesey is formed of schists and gneisses, while similar rocks occur in the Malverns (*Fig.* 116). In South Wales, the Pre-Cambrian rocks at St. David's are mostly volcanic in origin, including tuffs and lavas, into which a plutonic rock has been intruded; in North Wales (Carnarvonshire), in Warwickshire (Nuneaton), in Leicestershire (Charnwood Forest), and in Shropshire (the Wrekin and other hills south of it, near Church Stretton) volcanic rocks of similar character occur; while most of these can be shown to be of Pre-Cambrian age (for in some places Cambrian rocks rest unconformably upon them) they are not necessarily of the same exact age. In the Longmynd (Shropshire) occurs a vast thickness of sedimentary rocks of Pre-Cambrian date.

These inliers of Pre-Cambrian in Wales and England have been brought to the surface in the cores of sharp anticlines, often assisted by faulting. Frequently the Pre-Cambrian rocks are hard and often they stand out in conspicuous hills.

The almost complete absence of fossils from these Pre-Cambrian rocks is interesting, and several facts must be remembered in this connection. First these rocks are old, and many of them have suffered much metamorphism which may have destroyed any fossils formerly present (this would not apply to some of the unaltered sedimentary rocks, however); secondly, some of these rocks may have been formed before life appeared on the earth, or when the primitive animals had not acquired any skeletons likely to be pre-

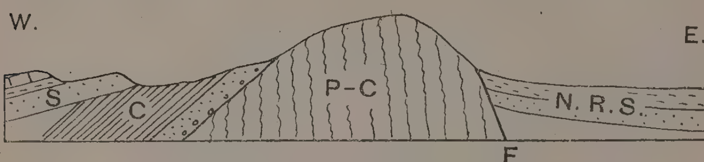


FIG. 116. A diagrammatic section through the Malvern Hills. P-C, Pre-Cambrian; C, Cambrian; S, Silurian; N.R.S., New Red Sandstone.

served; the presence of occasional worm tracks suggests that the earth was not wholly devoid of life throughout the Pre-Cambrian.

The Lower Palæozoic Rocks. The Lower Palæozoic rocks include the Cambrian, Ordovician and Silurian. These three Systems consist of marine deposits, chiefly sandstone and shale (often altered to slate). The Ordovician differs from the other two in including many volcanic rocks: it represents a period of great volcanic activity, when lavas and ashes were ejected by numbers of volcanoes, mostly submarine.

The three Systems occur to some extent in the same regions: they are best represented in Wales (from which country all three derive their names, Cambria being an old name for Wales, and the Ordovices and Silures being tribes

which inhabited parts of Wales); they make up the whole of the central and northern parts of that country. The Ordovician and Silurian also occur together in the Lake District and in the Southern Uplands; all these areas consist of high ground and they have many scenic features in common. The Cambrian and Silurian are also found in small areas in western England (the Malverns, Shropshire), and the Cambrian as already noticed is present in the north-west of Scotland.

The fossils of these three Systems consist mainly of Trilobites, Brachiopods and Graptolites (these latter appeared near the end of the Cambrian and lasted till late Silurian time). Corals, crinoids and other invertebrates are abundant occasionally, being especially common as fossils in the limestones. Many of the shales and slates are very deficient in fossils and contain little except graptolites: many were probably formed away from the shore lines where the shelly faunas lived.

The Cambrian Rocks. The Cambrian is seen resting on the Pre-Cambrian in several of the areas where those rocks occur, and it always does so with marked unconformity. That is to say, towards the end of Pre-Cambrian times the surface underwent denudation prior to the deposition of the Cambrian, which marked the initiation of a new sea by the submergence of a wide area. This sea lasted with minor changes till the end of the Silurian period.

Cambrian rocks occur in Wales at St. David's and in the Harlech Dome. At the latter place the base is not seen, but a great thickness of slates, flagstones and sandstones dip outwards to north, east and south under the Ordovician rocks. The sandstones give rise to barren uplands, but the softer slates form more fertile belts (*Fig.* 117). The Cambrian rocks of England (near the Malverns, and in Shropshire and Warwickshire) are thinner and include much soft shale, not converted into slate: they give rise to no striking scenery.

The Ordovician Rocks. Ordovician rocks are very widespread in North Wales. Their most important occurrences are in the mountain ring around the Cambrian of the

Harlech Dome. The great hardness of the volcanic rocks and the associated sills leads to them standing out as strong escarpments, such as Cader Idris: Snowdon to the north consists of these rocks folded in a syncline (*Fig.* 117).

In South Wales there are fewer volcanic rocks and the hills are not so high, but in the Lake District vast thicknesses of lava and ash give rise to Helvellyn, Scawfell and other craggy mountains. Ordovician rocks form the northern part of the Southern Uplands. Apart from these larger areas, the Ordovician rocks do not occur in so many places as the Cambrian and Silurian.

The Silurian Rocks. Silurian rocks give rise on the whole to a much gentler type of scenery than the Ordovician owing to the absence of volcanic rocks, but they nevertheless

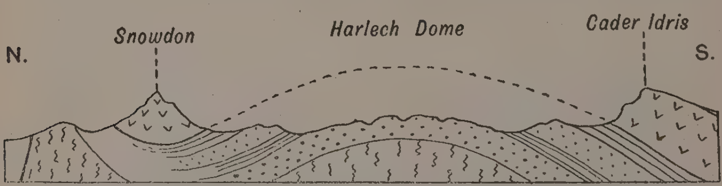


FIG. 117. A section across North Wales showing the Cambrian rocks overlying the Pre-Cambrian (wriggly lines) and overlain by Ordovician (marked by VV).

form moorlands, often of rather monotonous aspect, for example in Central Wales, Denbighshire, the southern part of the Lake District and the Southern Uplands. In these areas they are mostly dull grey sandstones, greywackés, and shales or slates, but in Shropshire and near the Malverns there are limestones among the shales which form distinctive escarpments such as Wenlock Edge.

A Mountain-Building Episode (*Caledonian Folding*). Although there had been slight earth movements causing folding of the rocks during the time represented by the Lower Palæozoic, it was not until near the end of that time that great folding movements occurred, bringing to an end that long marine episode. Folding went on intermittently for a time during the early Devonian, and the

total effect was to raise the sediments of the Cambrian, Ordovician and Silurian into a great range of mountains. The folds run from north-east to south-west, and the mountains must have had the same general direction. The folds now present in North Wales, the Lake District and the Southern Uplands date mainly from this time, and show this direction.

Obviously, deposits could no longer be formed in the same area when the sea was replaced by mountains, and denudation of the upraised folds continued there for a long time, in many parts throughout the Devonian. Denudation at that time and subsequently has removed the Silurian from the anticlinal areas, so exposing the older rocks. The date of these earth movements has been fixed, it must be realised, by the fact that rocks newer than the Silurian are in general unaffected by these folds, and rest unconformably on the Lower Palæozoic rocks.

The distribution of land and water was thus quite different in Devonian times from what it had been from the Cambrian to the Silurian.

The Devonian Rocks. Devonian rocks of marine origin are only found in Devon and Cornwall: there they occur in two areas on the north and south limbs of a great syncline; one area covers Exmoor and North Devon, the other is in South Devon and Cornwall. The rocks in the north are mostly sandstones, grits and shales (changed usually to slates); in the southern area there are in addition thick limestones around Torquay and Plymouth, and also lavas. Fossils are not common except in the limestones, which contain many corals: brachiopods and trilobites are also present.

Elsewhere in Britain the only rocks formed during this period were laid down in inlets of fresh water or in lakes amongst the mountains and on their borders: these rocks contain no marine fossils, but primitive fishes occur; as some of these fishes apparently spent part of their time also in the sea (as does the eel, for example, at the present day) they are found in both the marine and the non-marine deposits, thus confirming their correlation.

The non-marine deposits are generally red in colour, and consist of sandstones, conglomerates and marls. They are known as the Old Red Sandstone. This group covers a wide area in Herefordshire and Brecknockshire, where the conglomerates form an escarpment in the Brecon Beacons, the marls giving rise to more fertile country (*Fig.* 118a). This area of Old Red Sandstone was formed in a basin quite separate from others further north. One of these covered the area where the Cheviots and the Midland Valley of Scotland are now, another the area of north-east

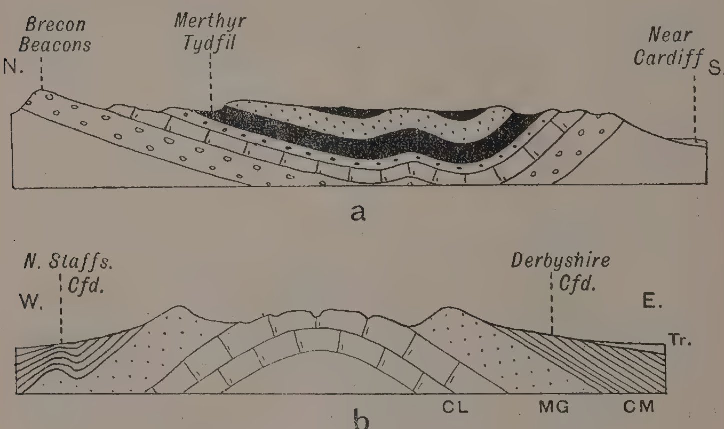


FIG. 118. A section across the eastern end of the South Wales Coalfield. The rocks shown are Old Red Sandstone (the conglomerates indicated), Carboniferous Limestone. Millstone Grit and Coal Measures (black, with the Pennant Sandstones dotted): New Red Sandstone unconformably in the south. b, A section across the Pennine area. CL, Carboniferous Limestone; MG, Millstone Grit; CM, Coal Measures; Tr., Trias.

Scotland, including the Orkneys. In the Cheviots and the Midland Valley the Old Red Sandstone includes lavas (rhyolites, andesites and basalts), tuffs and agglomerates, which form high ground.

The Carboniferous Limestone. The Carboniferous rocks are divided as follows—

Upper Carboniferous { Coal Measures.
Millstone Grit.
Lower Carboniferous, Carboniferous or Mountain Limestone.

In many parts the Carboniferous Limestone differs so much from the higher rocks of the same System that it is useful to consider it separately. It is essentially a limestone group, from the Mendips to Yorkshire consisting mainly of massive grey limestones. Further north the group often contains more shale and sandstone, and in Northumberland and the Midland Valley it also contains coal seams. There was some volcanic activity during the period, most important in Scotland where sheets of lava some thousands of feet thick spread over wide areas (as in the Campsie Fells).

It is obvious from a glance at a geological map that the Carboniferous Limestone was laid down over a much wider area than the Devonian; the Carboniferous thus overlaps that system, and so in many areas it rests unconformably on a denuded surface of Lower Palæozoic rocks. The Carboniferous Limestone is of marine origin, so it follows that this overlap resulted from the sea once more spreading northwards across the area which is now Britain: this converted the Old Red Sandstone areas into arms of the sea, and covered many other areas.

The fossils of the Carboniferous Limestone are chiefly corals, brachiopods and crinoids. The scenery of the areas occupied by these massive "mountain" limestones has already been described in Chapter II.

The Millstone Grit. The Millstone Grit is best developed in Yorkshire and Lancashire. There it consists of felspathic sandstones and coarse grits alternating with shales. The sandstones are often pebbly and current bedding is common. They represent shallow water deposits laid down probably as deltaic material by a river or rivers flowing from the north. Many of the shales contain marine fossils,

chiefly goniatites and lamellibranchs which replaced the corals and crinoids as the waters became muddy.

The Millstone Grit of Yorkshire forms high moorland, each grit band standing out as a scarp edge (compare *Fig.* 118b). Elsewhere the Millstone Grit is much thinner. The rocks of that age in parts of South Wales consist largely of shales, but they contain the same goniatites. Quartzite is present in places in that area, as also near Bristol.

The Coal Measures. The rocks of the Coal Measures are chiefly shales and clays, but sandstones are also frequent; in many areas these occur chiefly near the base, while in South Wales a thick sandstone group (the Pennant Sandstone) occurs near the middle of the succession (*Fig.* 118a). Coal seams form only a small proportion of the Coal Measures.

The Coal Measures were laid down over an area even wider than the Carboniferous Limestone and Millstone Grit, for they overlap them in some places. Most of the areas now occupied by England and Wales and southern Scotland were thus once covered by Coal Measure sediments.

The flora of the Coal Measures is very well known (p. 191): the fauna included fishes and some amphibia, insects of various types, and, most abundant of all, fresh-water lamellibranchs (*Carbonicola*) which occur in many shales. These rocks were thus laid down mainly in fresh-water tracts, which from time to time became so shallow that forests covered them and gave rise to the coal seams. These tracts were almost at sea level, for they were occasionally invaded by the sea, forming thin marine bands in which goniatites and *Lingula* are abundant.

Mostly the clays of the Coal Measures form low country, but the sandstones give rise to higher areas and the Pennant Sandstone in South Wales forms a high plateau.

Another Mountain-Building Episode (*Armorican Folding*). At this stage there was another interruption to sedimentation, and the Devonian and Carboniferous rocks were in turn involved in mountain building. Pressure was greatest in the south, and there it produced anticlines and synclines running from east to west; the fold in Devon and

the South Wales coalfield (*Fig.* 118a) are examples of synclines, the Mendips of an anticline. In the north, folds with a north-south direction were also produced (*Fig.* 118b). After these earth movements denudation again became active. As the Coal Measures were the highest beds in these folded rocks, they suffered first, and were worn off all the anticlines; so the various coalfields became detached from one another and Coal Measures are only found now in synclines.

New Red Sandstone (Permian and Trias). The red rocks of this group may be compared in many ways with the Old Red Sandstone: both followed a mountain building period, and in each case deposition started in limited inland basins. The earliest deposits had no great extent, but the later overlapped them; there is a widespread unconformity beneath the New Red Sandstone.

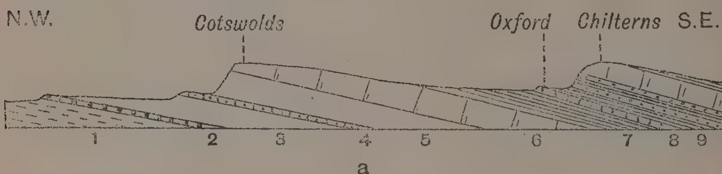
The Permian was laid down in detached basins. In Durham the Magnesian Limestone is occasionally fossiliferous, but elsewhere unfossiliferous red marls and conglomerates predominate.

The lower part of the Trias is known as the Bunter Sandstone, which includes some pebble beds. It is current-bedded and probably of deltaic origin (*Fig.* 69). Fossils are very rare. The upper part of the Trias, the Keuper, consists mainly of red marl with some sandstones: it overlaps the other divisions and is more widely distributed. It forms much of the Midland and Cheshire plains. The lower part of the Keuper is of fresh-water origin, and it contains occasional fossil fishes, but the upper part is devoid of fossils, and has salt pseudomorphs, beds of gypsum and (in Cheshire and Worcestershire) deposits of rock salt: in brief, the lake became a salt lake in which these minerals were precipitated. These later Keuper deposits contain no fossils; the conditions may have been of desert character.

The Jurassic Rocks. Just as the Carboniferous sea invaded the Old Red Sandstone lakes, so the sea spread over the Keuper areas at the beginning of the Jurassic. The first division of the Jurassic rocks (the Lias) consists mainly of blue clays, typical marine muds, with some ironstones and

thin limestones. These rocks form a belt of low country, to the east of the Keuper plain, stretching across England from Yorkshire to Dorset.

Above the Lias come the limestones known as the Oolites, probably formed in shallower and clearer water than the Lias. They include the Bath Oolites and form the escarpment of the Cotswolds, dipping gently eastwards under the clays which occur above them: these latter are rather similar to the Lias, forming the low ground about Oxford and in the Fens (*Fig.* 119a).



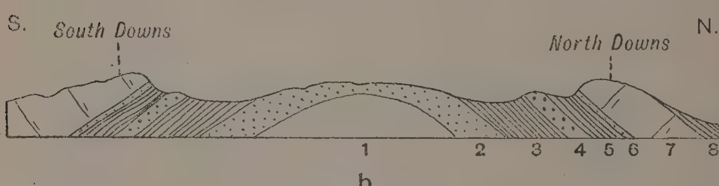


FIG. 119.

a. A section from the Midland Plain to the edge of the London Basin.
1, New Red Sandstone; 2, 3, Lower Lias; 4, Middle Lias (Ironstone); 5, Upper Lias; 6, Oolite; 7, Oxford Clay; 8, Corallian Limestone; 9, Kimmeridge Clay. The Chalk forms the Chiltern Hills.

b. A section across the Weald.
1, Jurassic; 2, Wealden Sands; 3, Weald Clay; 4, Lower Greensand; 5, Gault Clay; 6, Upper Greensand; 7, Chalk; 8, Lower Tertiary.

The Jurassic rocks are particularly rich in fossils, ammonites, belemnites, and lamellibranchs being very common, together with corals, echinoids and the brachiopods *Terebratula* and *Rhynchonella*. Reptiles are most com-

monly represented in the Jurassic rocks of this country by the aquatic forms.

The Cretaceous Rocks. Before the end of the Jurassic period an uplift of the region led to the withdrawal of the sea from most of England, deposition being continuous only in an area (mainly of fresh-water) in the south-east. The sea re-entered the Yorkshire area at the beginning of the Cretaceous, but the earliest Cretacous rocks in the south-east were formed in fresh-water (the Wealden Beds). The sea in which the succeeding Greensands and Gault Clay were deposited covered a wider area. Finally in an extensive sea under remarkably uniform conditions the Chalk, the most familiar deposit of the Cretaceous, was laid down.

In general, the Cretaceous rocks now outcrop to the east of the Jurassic, which dips eastwards under them (*Fig.* 119a). But the Cretaceous rocks have not quite the same simplicity of outcrop as the Jurassic, for they are involved in a series of denuded folds in south-east England (*Figs.* 119b, 130e). The Chalk gives rise to downlands, rising in the Chilterns to a scarp which is parallel to the Cotswolds, and also forming the North and South Downs.

The Cretaceous fossils belong to much the same groups as those of the Jurassic.

The Lower Tertiary Rocks. The Lower Tertiary is represented in the south-east of England in two synclinal areas, the Hampshire basin (including the north of the Isle of Wight) and the London basin, separated by the anticline of the Weald. The rocks in these areas are mostly soft sands and clays, partly of marine and partly of estuarine origin: the marine clays are very rich in fossils, particularly gastropods and lamellibranchs very much resembling many living genera.

While these rocks were being deposited in the south-east, there was very pronounced volcanic activity in northern Ireland and along the west of Scotland; in particular, enormous thicknesses of basalt lava were then poured out, of which the Giant's Causeway in Antrim is but a relic. Numerous intrusive rocks (including many dykes) in those areas date from the same time.

The Alpine Mountain-Building. There are no Miocene deposits in Britain, but at about that time there was a period of intense crustal movement which led to the uprising of the Alps and of other mountain chains in southern Europe. Britain was too far from the areas of greatest disturbance for rocks to be folded so intensely as others had been in earlier earth movements, but the Cretaceous and Lower Tertiary rocks of southern England were folded into synclines and the anticline of the Weald, while probably the form of other parts of Britain was considerably modified. This was the last great folding movement in our history, and Britain since that time has only undergone minor changes in its pattern.

The Pliocene and Later Rocks. Britain still remained linked to the Continent, however, and thus the North Sea was only a gulf, into which the Thames and Rhine flowed. Along its western shores, the banks of shell gravel and sands which were laid down now form the coastal part of East Anglia, but elsewhere there are no extensive Pliocene deposits, and the period was mainly one during which our present rivers were developing their valleys. As the land in many parts was some 400 feet lower than at present, the rivers formed peneplains with this base-level, while around our coasts, wide wave-cut platforms were carved by the sea (*Fig.* 49). These have since been uplifted, in several steps, river terraces and raised beaches marking stages in the course of the uplift.

This uplifting continued until the time of the Great Ice Age, which occupied much of the Pleistocene. Ice spread over most of Britain as far south as the Bristol Channel and Thames: during several warmer periods it retreated, only to re-advance. Its deposits and its effects on scenery have already been noticed. It may be suggested that the denuding agents are in many cases little more than beginning the task of removing the debris left behind.

Summary of Geological History. It may seem that the geological history of Britain is long and involved. Long it certainly is, for it represents many hundreds of millions of years. But the various stages may be summarised by re-

calling the several cycles of deposition, earth-movements and denudation which have occurred. The advance of the sea over Pre-Cambrian land surface initiated a marine episode which lasted till the end of the Silurian, when great earth-movements caused the folding of these deposits, and denudation followed in the Devonian. The new period of deposition started in the Devonian continued over widening areas in the Carboniferous, to be brought to an end again by the folding of the newly-formed rocks, with denudation in the Permian and Trias. The Mesozoic deposits spread over the area once more, and with a reduction in extent, deposition continued in the early Tertiary, but the Alpine movements again changed the conditions.

It will be useful for the student to note that the rocks corresponding with every one of these cycles begin with unconformable deposits; the Cambrian is unconformable on the Pre-Cambrian, the Devonian and Carboniferous on the Lower Palæozoic, the New Red Sandstone on some member of the Palæozoic, the Pliocene and Pleistocene on Lower Tertiary or something older. It is by the interpretation of these unconformities that part of this history has been revealed and the dates of the mountain-building episodes have been fixed. Although these latter are shown to have characterised certain times in earth history, it must be understood that each mountain-building episode probably occupied millions of years, and that the folding may have taken place very slowly.

SUGGESTIONS FOR PRACTICAL WORK

Geological sections may usefully be drawn across parts of the British Isles map (see p. 138).

The distribution of the various systems will be emphasised if separate outline geological maps are coloured for each system.

QUESTIONS

1. Describe the Lower Palæozoic (or the Mesozoic) rocks of England and Wales, and indicate the scenic features to which they give rise.
2. How would you endeavour to ascertain the age of a geological formation? (C.W.B.Hr., 1933.)

3. State the nature and disctribution of *either* (a) the Chalk *or* (b) the Carboniferous Limestone, mentioning some of the characteristic fossils. (C.W.B.Hr., 1934.)
4. State how Great Britain is divided into a number of natural geological regions and mention the geological systems represented in each area. (C.W.B.Hr., 1936.)
5. Describe some of the fossils found in coal-bearing rocks, and explain how the fossils came to be in such rocks. (C.W.B., 1933.)
6. Give a list of the chief formations in Britain which were *not* formed under marine conditions. Briefly explain the mode of origin of *two* of them.
7. How far do fossils afford evidence of the conditions under which the rocks containing them were laid down? Give examples from any *three* formations. (C.W.B.Hr., 1927.)

CHAPTER XIII

OTHER ASPECTS OF LAND FORM AND STRUCTURE

River Systems. In many areas the rivers and streams appear to present a reasonably simple pattern, many flowing in parallel directions; on the other hand, in other areas the pattern may at first seem very complicated, but even in such cases careful study of the more frequent directions of flow will often make it possible to detect some underlying regularity.

This systematic arrangement of neighbouring groups of rivers results primarily from the conditions under which the rivers first began to flow, though it may have been modified owing to the influences of the rock structure over which they flow. Numbers of rivers in southern and eastern England are seen to follow a direction which is usually the same as that of the dip of the rocks. It is probable that many of these rivers represent streams which were developed on a sloping surface formed by an uplifted and tilted sea floor when the greater part of England was raised from below the sea, probably in the Cainozoic. At that time the rocks were given the dip to the east and south-east which characterises much of central England, and the rivers which were then initiated took roughly parallel courses down the slope to the sea. It will be useful for the student to spend some time examining geological maps of England to verify this statement; he should note the Upper Thames and its early tributaries and the rivers of West Yorkshire.

Such streams are called *consequent* streams, since their direction was consequent on the tilt of the surface on which

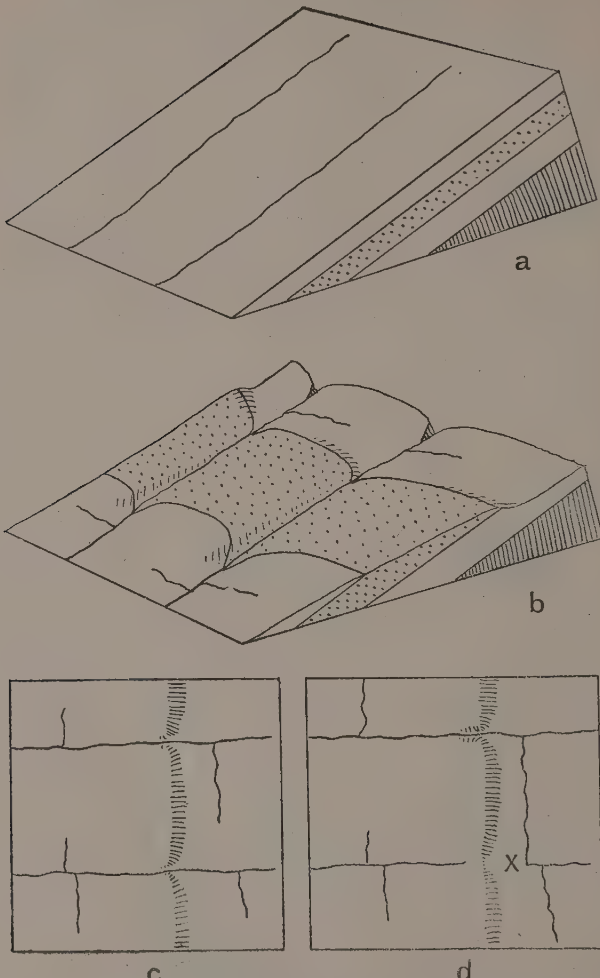


FIG. 120. Stages in the development of a river system. a, consequent streams; b, development of subsequent streams and of an escarpment; c, the same in plan; d, a later stage with river capture at x.

they began to flow. River systems newly established on any fairly uniform surface must always have consisted mainly of groups of such parallel consequent streams. At first it will be realised that streams may have flowed throughout their courses on one bed (*Fig.* 120a), but as they deepened their valleys, most cutting necessarily being done in the more elevated regions away from the coast, they came to flow on different beds at different places, starting on older rocks and flowing (with the dip) on to newer (*Fig.* 120b). Many English rivers do this now.

As the consequent rivers flowed across beds of different type (and presumably of different degrees of resistance to erosion) the valleys became wider in the softer beds than elsewhere: on the outcrops of these softer beds weathering was also more effective, so that these areas were lowered. Tributaries began to develop chiefly on these tracts with their courses along the strike of the rocks and at right angles to the courses of the consequent (or dip) streams. These tributaries are known as *subsequent* (or strike) streams (*Fig.* 120c). Owing to their situation on more easily eroded rocks the subsequent streams cut down their beds very rapidly, and frequently a subsequent stream has succeeded by headward erosion in capturing the headwaters of one or more neighbouring consequents (*Fig.* 120d). As a result, the main drainage in many areas tends to be along the strike, and the original streams, the consequents, often appear only as tributaries to greatly enlarged subsequents. The outcrop of the New Red Sandstone, an easily eroded group, is followed by several important rivers which are subsequent streams for at least part of their courses (*e.g.* the Yorkshire Ouse, the Trent, the lower Severn).

The excavation of valleys along the outcrops of softer rock groups (which may be known as *strike valleys*) partly by weathering and partly by river erosion, is an important factor in the formation of escarpments (see *Fig.* 120b, c).

The arrangement of rivers does not always conform to this simple rectangular pattern; some of the factors which may lead to modifications are dealt with below.

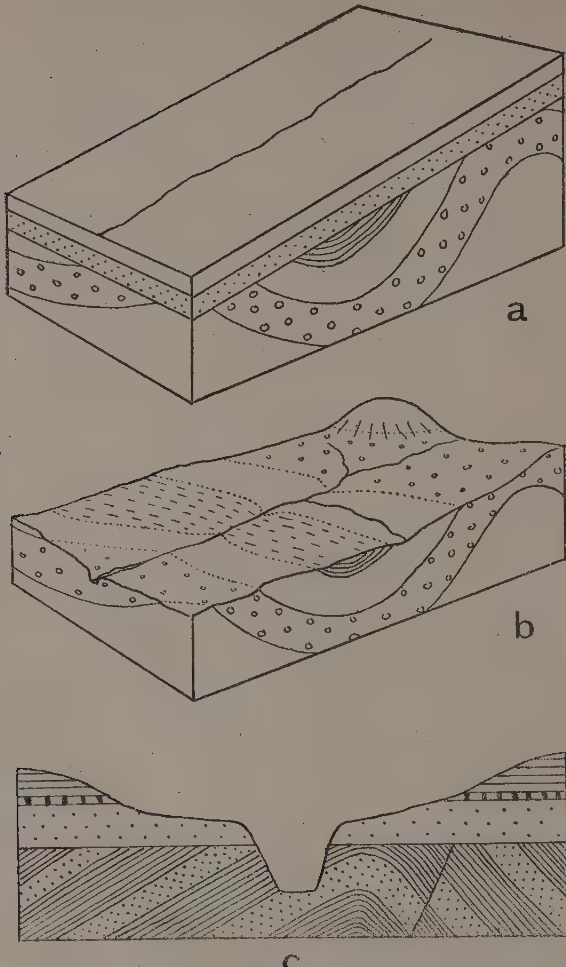


FIG. 121. Diagrams to show superimposed drainage. a, consequent stream on a gently dipping series; b, the same area after the removal of the upper group of rocks; c, section across the valley of the River Chew, near Bristol, showing a stream which has just become superimposed.

Superimposed Drainage. Drainage is said to be superimposed when a system of rivers developed on one group of rocks has cut down through them on to older rocks with a different (and often more complex) structure. This is illustrated in *Fig.* 121a, b. The consequent rivers initiated on the gently dipping rocks of the upper group, together with any subsequent tributaries which may have developed, have cut their way down to the rocks on which the upper group rested unconformably; for some time the rivers may continue without substantial changes in their courses. Thus the originally consequent and subsequent streams have not any of the normal relations to the dip and strike of the beds on which they flow. In Wales the rivers are typically superimposed. In South Wales many parallel rivers flow from north-west to south-east across the structures of the coalfield; their parallelism suggests that they are consequent streams, but they flow across folds and faults and have no apparent relation to the present structures; the drainage was probably developed on newer rocks which have almost completely disappeared. In the Bristol district an interesting stage in river development is seen, for there the rivers are flowing partly on the gently dipping Mesozoic rocks, and partly on the complicated Palæozoic rocks (on which the Mesozoic rocks rest unconformably); thus the rivers partly show normal relations and are partly superimposed, some having just cut through the Mesozoic cover (*Fig.* 121c).

In the Lake District the position is rather more complicated. There the consequent rivers were developed on a dome of newer rocks and thus had a radial arrangement; this has become superimposed on the very intricate structures in the Ordovician and Silurian rocks. The main valleys still retain their general pattern, however, radiating outwards from near Scawfell.

Lakes. The origins of various types of lakes have been mentioned in several previous chapters: the various modes of formation are summarised here, and one or two types not before mentioned are referred to. There are three main groups:—

1. Lakes due to a dam of some kind, usually blocking a river valley. Included here are lakes formed by an ice dam (Lake Pickering), a moraine dam or boulder clay dam (pp. 69, 70), and by screes, landslips and flows of lava; lakes formed by wave-built dams at river mouths (p. 80) or by dams of sand dunes; ox-bow lakes (p. 44).
2. Lakes due to erosion. The most important are the rock basins due to ice action (p. 65); there are also lakes resulting from solution, especially of limestone and of rock salt, many of the *meres* of Cheshire being examples in the latter case.
3. Lakes due to earth-movements. Movements of the earth's crust causing the tilting of regions have probably been responsible for some rivers failing to reach the sea by their former routes, and so for the formation of lakes. The Dead Sea and the great African lakes are related to the formation of rift valleys (see p. 217). Craters of dormant or extinct volcanoes are sometimes occupied by lakes, as in the Eifel district.

It may be noted that lakes are generally rather temporary features of a landscape; sooner or later they are either drained or become silted up with deposits to form level tracts of alluvial material.

Faults and Land Forms. When a fault was first formed it may have given rise to a step-like feature running fairly straight across the country. Such features are known as *fault-scarps*. They have been formed in some earthquakes (see p. 222). Such scarps do not remain for long as prominent features in the landscape, for the sharp edge formed by the upraised strata is in time worn down. Ultimately most fault features may have been worn down to a fairly level surface. Any change of level which now is found at the line of fault has in many cases been produced later by erosion: such a fault scarp results from the fact that on either side of a fault line beds of different age (and often of different resistance to erosion) are brought together: the side consisting of more resistant rocks tends to stand out,

its edge being a fault scarp (or, more precisely, an *erosional* fault scarp). The differences between such a scarp and an ordinary escarpment due to dipping beds should be noticed: a fault scarp is usually straight, and is not usually backed by a dip slope; it never has outliers, and its direction is not necessarily the direction of strike.

Fault scarps are most frequent where faults separate areas consisting of generally resistant rocks from areas of much softer rocks. The north-south line running under Cross Fell, which separates the Alston Moors (Carboniferous) from the Vale of Eden (New Red Sandstone) is a well-known English example: the east face of the Malverns (Pre-Cambrian against the New Red Sandstone) is another (*Fig.* 116).

In Scotland two main fault scarps bound the Midland Valley; one, the Highland Boundary Fault, extends from Stonehaven south-westwards to the Firth of Clyde and separates the Pre-Cambrian of the Grampian Highlands from the Old Red Sandstone and Carboniferous rocks, the other, the Southern Upland Fault, separates these latter rocks from the folded Ordovician and Silurian strata of the Southern Uplands. The block of country forming the Midland Valley or Lowlands, some fifty miles wide, has thus been "let down" between the two great faults; it may thus be thought of as due to trough faulting (*Fig.* 115). Such a down-faulted block having lower relief than the bounding blocks is also known by the German word *graben*. Another smaller example in Britain is the Vale of Clwyd in North Wales, in which New Red Sandstone is let down between Carboniferous and Silurian tracts. In eastern Africa, a narrow down-faulted belt known as a *rift valley* extends through the region occupied by the narrow lakes Albert Nyanza, Tanganyika and Nyassa, while another branch contains lakes Rudolf and Stephanie; northwards the rift extends along the Red Sea, the Dead Sea and Jordan valley. Everywhere along the rift a strip of country has been let down between nearly parallel faults (sometimes a series of step faults is present on either side); in the Dead Sea the region has been dropped far below sea level.

In a similar manner, blocks of old and resistant material

have in some cases been left standing up, separated by faults from lower tracts of newer rocks; such up-faulted areas are known by the German word *horst*. The Black Forest forms such an area, rising above the rift-valley occupied by the Rhine.

Faults do not always give rise to scarps or bound tracts of high relief, however. Where dip faults cross lower ground they may cut off the small escarpments formed by the harder beds, and so influence relief. In other cases faults may give rise to long narrow depressions, for since a fault represents a plane of weakness, and in some cases a belt of more or less shattered rock, it is not uncommonly excavated to form a hollow. The most impressive example in Britain is the Great Glen, extending in a straight line through the lochs from Loch Ness to Loch Linnhe. On a smaller scale, the valley which holds Bala lake in North Wales and the Vale of Neath in South Wales are fault-valleys. It will be noted that a fault valley may be occupied by a river or rivers which have cut down rapidly in the weakened rocks and have captured the original drainage. Such fault belts may thus locally modify any existing river system.

Topography of Areas of Folded Rocks. It has already been pointed out that anticlinal areas do not long remain as ridges nor synclinal areas as valleys. Many folded regions have been planed down by denudation. On these plains the outcrops of harder rocks may stand out as the less resistant rocks are worn away more rapidly, the pattern of the ridges so formed depending closely on the amount of dip, the nature of the folds, and the pitch.

It often happens that an area of folded rocks which has long been exposed to denudation has the synclines forming the hills while the anticlines have become worn down below the general level (*Fig.* 80b). This weakness of the anticline is generally regarded as resulting from the fact that in the rocks of an anticline the joints are pulled open on the outside of the fold, whereas in the synclines they tend to be pressed together (*Fig.* 122). Among mountains of synclinal structure, Snowdon is a good example (*Fig.* 117).

Plains and Plateaux. There is a close relation between plains and plateaux, for many plateaux are really plains which have been elevated (sometimes at no distant geological date). Plains have been formed in many different ways, but may be considered in two groups, *viz.*, those due to denudation and those due to deposition.

Plains due to denudation include the peneplains formed by sub-aerial erosion and also plains of marine denudation: when these have been uplifted it is not always possible to tell the precise mode of origin, for both types usually cut across the edges of the beds with little regard to variations in hardness. Plains of marine denudation are often bounded inland by relics of old sea cliffs. The low coastal plateau around south-west England and the Welsh coast is an excellent example of an uplifted wave-cut platform (p. 83).

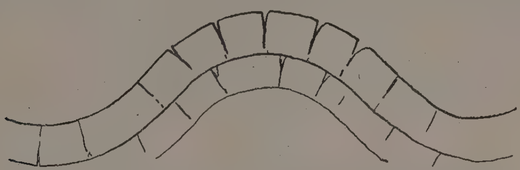


FIG. 122. Diagram of an anticline, to illustrate the supposed stretching of the top of the fold.

Plains formed by deposition include alluvial flats and deltas, fenlands and silted-up lakes and bays. Here also may be included those plains formed by volcanic accumulations. Widespread lava flows of great thickness may form plateaux, as in the Deccan plateau of India and in Antrim (p. 166).

Most plateaux (such as the Highlands and Central and North Wales) represent plains of erosion which have been uplifted, and their height depends primarily on the amount through which they have been raised. Their altitude is not simply a result of their resistance to erosion, for in a recently uplifted plateau hard and soft rocks alike form part of an even surface, which represents the level to which they were planed down. Once upraised, however, such areas are exposed to active denudation and gradually the rivers carve

valleys into them, while the areas of the original surface steadily decrease. The outcrops of the softer beds moreover tend to become etched out, leaving the harder bands to form ridges. Thus a plateau area, the relief of which at first showed little relation to its structure, may gradually develop escarpments and other features which reveal its structure until only the uniform level of its hilltops shows that once in its history it was a plain.

We may therefore trace a "Cycle of Erosion" in many areas which (1) have been worn down to a peneplain, (2) upraised to form a plateau, (3) dissected by river erosion, and (4) eventually converted into a peneplain again.

SUGGESTIONS FOR PRACTICAL WORK

Examination of the geological map of the British Isles (or of $\frac{1}{4}$-inch maps of south and east England), listing rivers which flow (a) with the dip and (b) with the strike of the rocks.

Construction of diagram maps to show the relation of drainage to geological structure, for example, in the Lake District and in South Wales. Other work on geological maps.

QUESTIONS

1. Describe the development of a typical river system on a newly raised land area. (C.W.B., 1936.)
2. What is meant by river capture? Explain how it occurs and the modifications in a river system to which it leads. Mention examples.
3. Summarise the ways in which mountains and hills have been formed. Name and illustrate some examples. (C.W.B.Hr., 1928.)
4. Explain the nature and mode of origin of *five* of the following:—outlier, corrie, incised meander, rift valley, atoll, escarpment. Illustrate your answer by diagrams. (C.W.B., 1934.)
5. Describe some of the ways in which lake basins have been formed.
6. Describe the topographic forms which may result from faults. Name some examples.

CHAPTER XIV

EARTH MOVEMENTS: EARTHQUAKES: SOME WIDER PROBLEMS OF EARTH STRUCTURE

Movements of the Earth's Crust. Evidence has been given in earlier chapters to show that considerable movements must have taken place in the earth's crust. Folding, usually resulting from compression, indicates that two points on opposite sides of the folded area have come closer together (see *Fig.* 79). Faulting in many cases marks

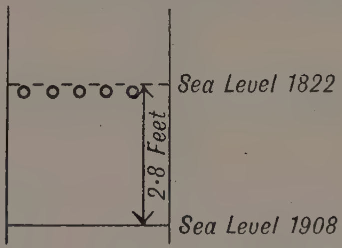


FIG. 123. Rise of land, Ulfö harbour, Gulf of Bothnia, between 1822 and 1908. (After DALY.)

the occurrence of "up-and-down" movements of parts of the earth's crust. That similar up-and-down movements may have occurred within comparatively recent geological times is suggested by the evidences of raised beaches and drowned valleys, and in some regions also by historical records; the shores of the Gulf of Bothnia have been raised by about 30 inches during the past century (*Fig.* 123). Many such movements appear to take place slowly, almost imperceptibly, but there is no doubt that if they were continued for a sufficiently long time they would lead to the emergence of new

land from beneath the sea or the spreading of the sea over parts of the land, and to changes like those recorded in the geological history of many areas.

Earthquakes. Probably the best-known movements in the earth's crust at the present time, however, are those sudden shocks which are known as earthquakes. Some of these are associated with volcanic activity, but the most disastrous of them appear to be quite independent of volcanoes. An earthquake results from a sudden movement, while most other movements in the earth's crust appear to take place slowly; possibly an earthquake is caused by a sharp break which occurs after a long time of accumulating strain in some part of the crust.

As a general rule, an earthquake does not give rise to features of great geological importance at the surface. In some cases fissures are produced, and occasionally, as in Japan in 1891 and in Assam in 1897, an actual displacement occurs, the country on one side being raised twenty or more feet above that on the other in a distinct fault scarp. Often landslips are also caused. Mostly, however, earthquakes are impressive for the damage they do to buildings and other structures; great loss of life is frequently caused, especially in towns, by falling materials and by the fires which follow. Some earthquakes are accompanied by loud noises, like distant thunder or a passing train.

An earthquake may be defined as the vibrations set up in the rocks of the earth's crust by a sudden displacement of material at some depth (not necessarily very great) within the earth. The displacement causing the earthquake cannot, of course, be observed; in its nature it is probably like a fault, but the amount of movement is probably not very great, and, as we have noted, the actual displacement only occasionally extends as far as the surface. The vibrations produced are of several kinds, but it is not necessary to describe their characters here; for the present it is sufficient to understand that these vibrations travel outwards from the place of origin of the earthquake, first reaching the surface of the earth immediately above, and then affecting an ever-widening area (*Fig.* 124a).

The place of origin is known as the *focus;* this is often thought of as a point, but in fact it is usually a line or plane, and may coincide with the deeper part of a fault plane. The earth's surface immediately over the focus is called the *epicentre* of the earthquake; in this neighbourhood the shock is felt most severely, while the intensity of the shock diminishes (in proportion to the square of the distance) at greater distances from the focus.

After many recent earthquakes, a study has been made of the distribution of the intensity of the shock over a wide

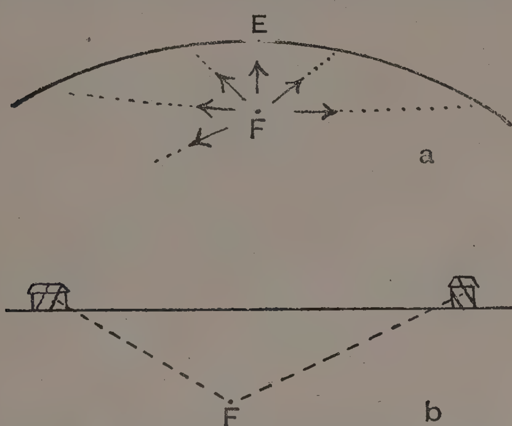


FIG. 124. a, Diagram to show the paths of earthquake waves from the focus (F); E, epicentre; b, diagram showing how the direction of cracks in buildings has been used to find the depth of the focus (scale greatly distorted).

area. This can conveniently be done by collecting information as to the nature of the damage done and of the effects noticed: after a severe shock an area can be delimited within which buildings cracked or collapsed, while around this may be an area where a great number of the chimney pots fell off but where little more serious damage was done, and outside this again an area in which crockery and windows were rattled. Using a somewhat more elaborate scale of

this kind it is possible after an earthquake to produce a map of relative intensities like the one shown in *Fig.* 125. The lines bounding the various areas, which may be regarded as lines connecting all points with equal intensities, are known as *isoseismal lines.*

In Britain severe earthquakes are very rare. Only on about six or seven occasions in the present century has any substantial damage been done by earthquakes. The Here-

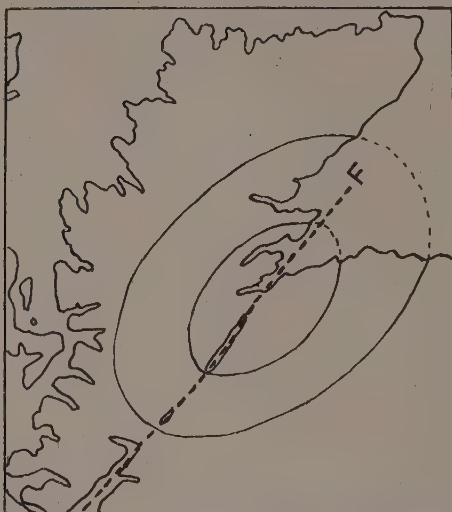


FIG. 125. Isoseismal lines of the Inverness earthquake, 1890. (After DAVISON.) F, shows the course of the Great Glen Fault.

ford earthquake of 1896 and the Swansea earthquake of 1906 may be mentioned; in Scotland earthquakes are most frequent in the neighbourhood of the great faults, notably the Great Glen fault (*Fig.* 125) and the Highland border fault. At Comrie on the line of the latter over 400 shocks have been recorded. This frequent association of earthquakes with

known faults is of great importance, showing the tendency of movement to be renewed along old lines of weakness. Many faults have probably been produced by repeated small movements of this nature.

Britain, however, is a relatively stable region, and it is in other areas, such as the Plain of India and the borders of the Pacific, that earthquakes are most disastrous. The earthquake of North Bihar in the Ganges valley in 1934 affected an area of almost 2 million square miles. In Japan earthquakes are of frequent occurrence, one in 1923 laying half of Tokyo in ruins and causing the death of a hundred thousand people. San Francisco suffered from a very severe shock in 1906 and New Zealand in 1931. Some quite important earthquakes have occurred under the sea, and have caused the breaking of submarine cables.

For a number of years attempts have been made to estimate the depth of the focus of earthquakes. Recently accurate means of doing so have been devised. An early method which gave reasonably good results depended on the observation of the directions of the main cracks produced in buildings: assuming that the cracks are usually at right angles to the impulse which produced them, by taking perpendiculars to large numbers of cracks in different places it is possible to gain some idea of the centre from which the impulses came (see *Fig.* 124b). In this and other ways the positions of earthquake foci have been found to lie generally at depths of less than twenty miles.

Earthquake Records. In the modern study of earthquakes much has been learned from records made by sensitive instruments which are capable of recording shocks at very distant places. Such instruments are known as *seismographs:* they are self-recording, a line being traced on a strip of paper moving at a known rate (somewhat as in the familiar barograph). When a shock occurs the movement causes the line to show a series of wriggles, and the time at which the shock reached the instrument is then known.

After the Japanese earthquake of 1923, for example, the first waves reached Hongkong 5½ minutes later, and in just over 8 minutes they reached Calcutta; within 12 minutes

they had reached England in one direction and California in another.

Earthquakes and the Inner Earth. From the point of view of the geologist, the most important results of the study of seismographic records relate to the light they throw on the inner structure of the earth. The geologist can only examine the accessible part of the crust, but earthquake waves travelling to distant seismographs must traverse

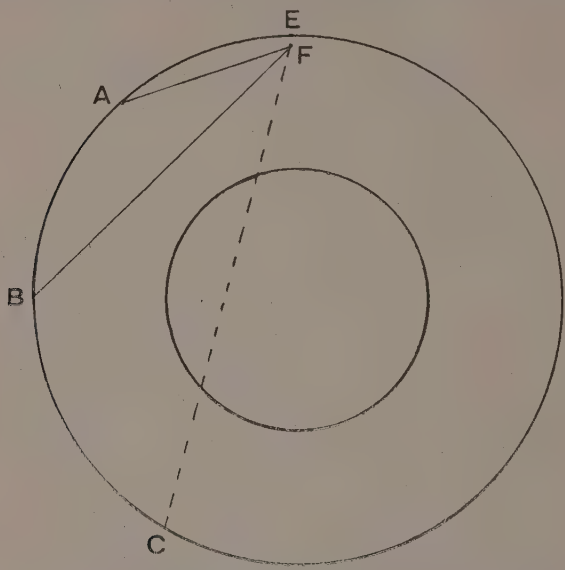


FIG. 126. Diagram to show the paths of some earthquake waves from a focus at F to various points on the surface, A, B and C. The metal earth-core is shown.

deeper parts of the earth; their behaviour and velocities afford information as to the character of those regions.

In *Fig.* 126 are shown the suggested paths of earthquake waves through the earth from a focus at F to points A, B and C on the surface at varying distances away. If the time of the shock is known, and the time at which the

shock reaches A is recorded, the rate at which the various waves travel through the earth from F to A can be calculated: similarly the rate from F to B may be known. In this way the rates of travel of the different types of earthquake waves through the shallower parts of the earth have been determined. When records of stations at greater distances from the focus (as at C) are considered it is found that different conditions prevail; one type of wave does not seem to pass through the inner part of the earth at all, while other waves are transmitted with velocities quite different from those they have in the outer part of the earth.

These and similar observations have led to the most important conclusion that the centre of the earth consists of a core having properties which differ greatly from those of the surrounding material. The radius of this core is believed to be a little more than half the radius of the earth. There are reasons for believing that it consists of some heavy material, probably iron or an alloy of iron and nickel; this view is supported by observations on the density of the earth.

Density of the Earth. The mean density of the earth as a whole has been calculated in several ways. One of the earliest attempts was made over hundred years ago, when a "torsion-balance" was employed; the description of the experiment is beyond the scope of this book, but the results obtained have subsequently been confirmed by more elaborate apparatus and in other ways. It is well established that the mean density of the earth is about 5·5 times that of water.

Yet the density of the rocks met with in the crust averages little more than half this; it therefore follows that the deeper parts below the crust must consist of material of higher density than the crust. A nickel-iron core, with a density probably more than 8 times that of water, would account for the mean density that has been determined. There are grounds for believing that beneath the lighter rocks of the crust is a more basic layer, with a composition similar to basalt, which in its turn is underlain by material of ultrabasic composition: there may thus be several concentric layers with density increasing with depth.

Temperatures of the Inner Earth. It is well known from a variety of observations that the inner earth is hot: the evidence of volcanoes and geysers points to the existence of extremely hot material below the crust. In mines it is known that the temperature increases with depth; the rate of increase varies in different areas, the temperature rising by about 30°C. for every kilometre of depth in Europe.

In many parts, at a depth of 50 kilometres a temperature of about 1,400°C. might be expected, which would be sufficient to fuse many rocks. It is believed that the rocks at this depth are kept from fusing, however, by the great pressure. A reduction of pressure at any place must lead to fusion (and thus to the production of magma and lava).

The Unstable Crust. The many changes which have taken place during the history of the earth (as shown by the record of the rocks) indicate that there has been, at least at certain periods, great instability in the earth's crust. It was formerly supposed that the cooling of the earth from a high temperature first led to the formation of a solid crust, and that as the interior continued to cool and thus to contract, the solidified crust became wrinkled to form the mountain ranges and other irregularities on its surface. This resemblance of the earth to a shrivelling apple is not so close as was once supposed, however; the vast periods of time which separated the great mountain-building episodes do not favour a belief in a gradual shrinking as an explanation of the origin of mountains.

One factor which probably leads to a change in the pattern of the crust is the removal from the land of vast quantities of material by the various agents of denudation and the deposition of this material as sediment in shallow seas. It is clear that if this process continued unhampered we might expect the land to be worn down almost to sea level (to form vast peneplains) and many of the neighbouring seas to be almost filled up by deposits. Although something very like these conditions has been established on several occasions during the history of the earth, it is apparent from what we know of geological history that movements in the earth's crust have led on several occasions to the eleva-

tion of such low-lying areas and so to the starting of another cycle of erosion (p. 220).

Some of the "up-and-down" movements of land masses may be accounted for by the theory of *isostasy*. According to this view, land masses consist of material of comparatively low density supported by a denser sub-stratum of the crust, which underlies continents and oceans alike; the land masses may be regarded as being in a state of balance, almost as though they were "floating" in the sub-stratum (although it must not be supposed that this stratum is liquid). Where a mountain group forms a large projection above the surface, there is generally a corresponding bulge downwards into the denser sub-stratum (*Fig.* 127). The remarkable

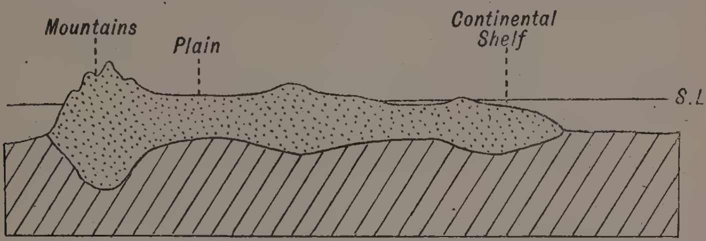


FIG. 127. Diagrammatic section to show the supposed form of a continental mass (dotted) in relation to the denser sub-stratum (shaded). S.L., sea level.

nature of the balancing of these land masses is strikingly shown by the fact that during the Ice Age the areas which were covered by thick ice accumulations sank down into the crust under the load; this is proved by evidence that the sea submerged the coastal tracts of those areas at that time, although sea level was actually lowered then (p. 81). When the ice disappeared these regions rose again. It is not surprising therefore that the denudation of an area causes it to rise, while the deposition of material in a shallow sea may cause the sea floor to sink.

Indeed, the deposition of a great thickness of sediment in comparatively shallow water implies the steady depression of that part of the earth's crust. Such a basin of de-

position thus forms a great downfold or *geosyncline*. Chains of folded mountains have generally arisen on the sites of geosynclines, the mountains being built from the sediments accumulated there (see pp. 200-1).

It is not certain, however, that up-and-down movements are the only factors in the modification of the earth's crust; some other possible factors are referred to below.

Problem of the Permanence of the Ocean Basins. The changes in distribution of land and sea which have occurred throughout geological history have mainly affected the continents and the shallow continental seas. Although many of the sedimentary rocks now forming the continents were originally laid down under the sea, nearly all of them are made up of sediments which accumulated in relatively shallow water, and not on the abyssal plain of an ocean bed. The Chalk which was once held by some geologists to be a deep-sea deposit (a consolidated ooze) is now believed to have originated in less deep water (p. 120).

The view has been widely held that the ocean basins have existed as such since the water first collected in them to form the oceans, and that in spite of all the changes in distribution of land and water around the continents most parts of the ocean bed have never been dry land.

On the other hand, the former existence of continents of which only fragments remain and of which the greater portions have sunk to form parts of the present ocean floor has been equally widely believed. One supposed continent has received the name of *Gondwanaland;* fragments of it remain in South Africa, Peninsular India, Australia and South America. Many believe that these were once linked into a vast continental mass, the greater part of which now lies in the floors of the South Atlantic and Indian Oceans. The fragments of this supposed Gondwanaland have much similarity in geological structure and history; one of the most remarkable features is the occurrence in all these areas of glacial deposits, representing an ice age which occurred very long ago, in late Carboniferous times.

Theory of Continental Drift. As against these views of permanent oceans and of vanished continental masses is

the more recent theory, first put forward by Wegener, of Continental Drift. To understand it, the suggestion made above that the continents are made of materials of low density held in a sub-stratum of denser material (of basaltic character) which underlies both continents and oceans must be borne in mind (*Fig.* 127). According to Wegener the continents are capable of drifting about in that sub-stratum. While the continental and oceanic areas are thus fundamentally distinct from one another, according to Wegener's view the continents are not now in the same relative positions as they were formerly.

To a certain extent the movement of parts of continental masses closer to one another is an essential factor in mountain-building; the Alps represent rocks which could only be crumpled up if Africa and Central Europe moved closer to one another than they were when the rocks were horizontal. But drift of the continents to the extent required by Wegener's theory is a different matter. His followers believe, for example, that the Americas were joined up to Europe and Africa (and that there was no Atlantic Ocean) until Cainozoic times; that the areas named above as supposed fragments of a vanished Gondwanaland were once in contact and have drifted apart; that continents may have changed their positions on the earth and so may have at times been near the poles, at other times near the equator, a view which would afford an easy explanation of major climatic changes.

In spite of the evidence which seems to favour this theory, however, and notwithstanding the very attractive way in which it enables us to solve so many difficult problems relating to land forms, climate, and the distribution of faunas and floras, it must be remembered that it is no more than a theory. Many objections have been raised against it, one being that there is no known force capable of moving continents in the basic sub-stratum. It is however an interesting speculation, and of some of its implications the student should be aware.

It may be summarised that the main problem of the major movements of the earth's crust is whether they have

nearly all been vertical or whether horizontal movements of the continents have played an important part. Considerable vertical movements have certainly occurred, elevating marine sediments to form high mountains, but there is some difference of opinion concerning the possibility of former continental masses having sunk to form part of the ocean floor, on the one hand, or of having drifted to different parts of the earth's surface, on the other.

Radioactivity and Geology. The discovery early in the present century of the nature of radioactive substances and the recognition of widespread occurrences of those substances in the rocks of the earth's crust have been of tremendous importance to geologists. Before that time the age of the earth was reckoned in tens of millions of years. Lord Kelvin, basing his calculations on the rate at which the earth is losing heat at present, estimated its age as about 25 million years. This period seemed to the geologists of that day far too short to afford time for all the known events of geological history and for the evolution of life.

Geologists attempted to estimate the age of the earth for themselves. Thus the maximum thicknesses of all the known sediments of different ages were added up, and an estimate made of the rate at which sediments accumulate at the present day, in order to determine the length of time required for the formation of the deposits. But as the deposits may not represent the whole period of time (unconformities for instance making gaps of unknown length), and as different rocks obviously accumulated at very different rates, the result was bound to be only very approximate. A period of something like 100 million years seemed to be indicated for the total thickness of sediment then recognised. Another estimate was based on the amount of salt in the oceans; since rivers carry salts into the seas, and since the seas probably consisted of fresh water when first formed, it was hoped to get some idea of the period taken by the rivers to carry in the salt now present; this depends on a number of assumptions, for example that the salt has been carried in at the same rate throughout the whole time, and that none

has been lost from the oceans in the meantime. Joly obtained a result of about 80 million years by this method.

In the first place the discovery of the radioactivity of certain substances quickly led to the abandoning of Kelvin's very limited allowance of time, since the heat generated in the earth's crust by the disintegration of radio-active substances could account for the loss of heat from the earth which the physicists had determined and which they believed to be due to its cooling: it became doubtful indeed whether the earth was getting cooler. But not only did it upset the data on which this estimate had been based; the discovery made possible an entirely new and much more reliable method of estimating not only the age of the earth but also of the rocks of different periods.

The radioactive elements uranium and thorium continually liberate energy which ultimately appears in the form of heat. As the elements give out this energy they change, atom by atom, at a slow but regular and known rate, into the stable elements, helium and lead. Thus radioactive minerals form a kind of hour-glass, running down at a regular rate, and the proportion of lead to uranium in a sample affords a measure of the length of time that has elapsed since its formation. By these methods it has been shown that the Cambrian period began over 500 million years ago, so that the age of the earth is not less than 1,000 million years; even this is to be regarded as a minimum estimate, and 3,000 million years is more probable.

In other directions the radioactive minerals may also be important, for the heat generated by them in the crust may cause liquefaction and expansion, and so may be a factor in producing igneous activity and earth movements.

SUGGESTIONS FOR PRACTICAL WORK

This Chapter deals mostly with material which lies outside the ordinary experience of students, and there is little practical work bearing on most of the problems. An experiment with blocks of wood of different thicknesses floating in a glass-sided vessel may help to illustrate the nature of isostatic balance.

QUESTIONS

1. Write a general account of earthquakes. What information concerning the internal structure of the earth has been gained from the study of earthquakes? (C.W.B.Hr., 1927.)
2. "Folded mountains have generally grown up on the site of a filled geosyncline." Discuss this statement and the movements in the earth's crust which are involved in the changes.

CHAPTER XV

SOME APPLICATIONS OF GEOLOGY

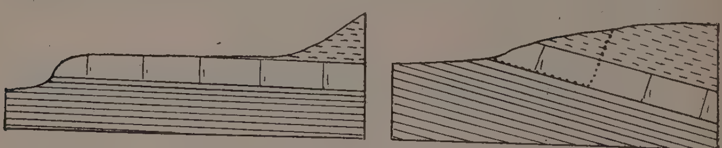
Geology and Practical Problems. In this chapter a brief reference is made to some of the more important applications of geology. It must first be emphasised, however, that in most cases where geological factors affect practical problems of engineering or the supply of materials, the data required are precisely similar to those which have been dealt with in preceding chapters. A knowledge of structural geology is essential in almost every case; ability is needed to read a geological map (and, if necessary, to construct one) in order to determine the amount of a given rock or mineral which can be worked at a particular place, and the shape of the mass. For instance, beds dipping very gently may outcrop over a wide area and can be dug in open quarries (as in many ironstone quarries in the east and middle of England), while a bed which dips more steeply can only be quarried to a limited extent owing to the steadily increasing quantity of "overburden" (*Fig.* 128b); below that depth it must be mined.

A knowledge of rock types and of the chief minerals is also indispensable, while some familiarity with fossils may be of enormous value. The use of fossils in determining whether given beds may contain coal or may overlie rocks containing coal has already been referred to (p. 193); in the still more detailed work of following individual seams in a colliery and of distinguishing one seam from another the fossils in the roof of each are of first-rate importance.

In this sense there is little "theoretical" geology; any fact may at some time prove of practical importance, whether in determining the depth at which solid foundations may be reached or at which some valuable material can be

mined, in controlling coast erosion or in selecting a site for a well. It may be mentioned that a large proportion of the raw materials of industry are obtained from the earth's crust, and in their exploitation all kinds of geological knowledge are required.

Rocks and their Uses. One of the most important uses of rocks is for building material. In different parts of Britain a great variety of rocks has been used for this purpose, for one of the most important factors in the selection of building stones is the nearness of supply. Formerly there was a quarry or a clay pit for brickmaking in nearly every parish, and the cottages at least were built from local material; more recently, with improved transport, material has been selected from places further afield (not always with happy results, for the "native" stone generally looks best



a b

FIG. 128. a, Section showing the wide extent of the outcrop of a nearly horizontal bed; b, a steeply dipping bed for comparison, showing the rapid increase of overburden and the probable limit of quarrying.

in any area). Lately the use of bricks and concrete has tended to diminish the use of stone except in a few more important buildings.

While nearly every type of rock, igneous, sedimentary and metamorphic, has been used in building, sandstones and limestones are the most important in use to-day. They are selected according to proximity to the site, according to colour and with reference to the size of blocks obtainable (p. 127). Attention should be paid to their durability; the presence of layers of clay or of minerals which are easily altered (such as iron pyrites) is undesirable. Limestones and sandstones with much calcareous cement may disintegrate rapidly in industrial towns, where there may be much

acid in the atmosphere. Many igneous rocks are polished for ornamental purposes (usually all of these are known commercially as "granite"); the metamorphic rock marble will also take a polish, and the term marble is similarly applied commercially to other limestones which are capable of taking a polish.

For roadstones, igneous rocks are largely used, the fine-grained rocks such as dolerite being particularly valuable for this purpose; some quartzites are also much used for road metal, while various other rocks, particularly limestones (such as those from the Carboniferous) are also quarried extensively for use in tarred roads, essential qualities in such material being resistance to crushing and ready adherence to tar.

Clays for brickmaking are widely distributed, those in the Coal Measures, Trias, Jurassic and Tertiary rocks being very important. Firebricks are commonly made from fire-clays of the Carboniferous (p. 116), but for other types of refractory material for the lining of furnaces both dolomite and quartzite are used. For making rough pottery many different kinds of clay are used; the china clay associated with the granite masses of Cornwall is used in the manufacture of porcelain.

Limestone is quarried for the manufacture of lime, for when heated in a kiln it loses its carbon dioxide and yields quick-lime, which is used for making mortar. Hydraulic or Portland cement, which is capable of setting under water, is made by heating a mixture of clay and limestone; in the lower part of the Lias and in some other formations, limestones and clays occur in alternating bands in a suitable proportion for use, but in other cases clay and limestone are mixed before burning. Plaster of Paris is made by heating gypsum (chiefly dug in the Trias of Nottingham and Derbyshire).

Sands also are necessary in the making of mortar, and for moulds into which molten iron is run in iron-works; for this purpose a slightly clayey sand is used, as it retains the form of the mould. Some Bunter sands are very suitable. For the manufacture of glass, quartz sands of great purity

and of uniformity of grain are required; some Cretaceous sands are excellent for the purpose.

Mineral Deposits. Some mineral deposits of economic value are sedimentary rocks; thus the ironstones of the Jurassic and the salt and gypsum deposits of the Trias are bedded rocks. Many mineral deposits form veins or irregular masses; in some cases they are closely associated with igneous rocks. Deposits of minerals of economic importance have been formed in a variety of ways, and examples of only the more important ways can be given here.

Deposits of some minerals, ores of iron, copper and nickel, occasionally form part of igneous intrusions. Such minerals are present in very small quantities in many different igneous rocks; where they are segregated it is in some cases due to the fact that they were among the first minerals to crystallise in the cooling magma, and that they sank to the bottom of the still liquid mass (as, for instance, to the base of a sill).

Occasionally, where a mineral is of sufficient value, it is worked in a mass of rock even though it has not been naturally concentrated. Diamonds occur scattered through the bulk of the altered igneous rock in the diamond "pipes" of Kimberley, forming no more than 1 part in 15 millions, yet the rock is as a whole crushed, the heavy minerals being separated out by washing away the lighter with water.

Some rare minerals have been freed from their parent rock and concentrated by natural means: particles of gold have been brought together in this way by the sorting action of streams on the disintegrated material from quartz veins or other auriferous rocks to form *placer* deposits (*Fig.* 129). Other placers contain diamonds or tinstone, and some occur as beach deposits.

Mineral veins may cut both igneous and sedimentary rocks. Many veins are clearly related to igneous masses even though they continue into the sedimentary rocks which surround them, and both the ore and the associated but worthless "*gangue*" minerals in the vein have in many cases been derived from the igneous magma. A cooling magma in a large intrusion, such as a boss, contains a pro-

portion of more volatile material which necessarily remains in the gaseous form after the bulk of the magma has consolidated: with these volatile constituents there usually remain also certain of the rarer constituents. Some of this residual material during the last stages of the consolidation of the magma collects in any cracks formed by the contraction of the cooling igneous mass, or finds its way into cracks in the surrounding rocks, and there crystallises.

The veins thus formed may contain coarse material (*pegmatite*) yielding large crystals of such minerals as mica

FIG. 129. Map to show Placer deposits (dotted) in relation to an ore-bearing vein (crosses).

and felspar. The tin and copper ores of Cornwall occur in veins which cut the granite and the surrounding slates; in these veins quartz, tourmaline and fluor spar occur as gangue minerals, while tinstone, copper pyrites, wolframite (tungsten ore), zinc blende and galena are frequently present, although not at one place in the vein; a single vein may contain different minerals at various depths. At any place the minerals on the margin of the vein are those which crystallised first, while those in the centre were formed in the later stages.

Beyond the region where minerals were carried in a gaseous state, certain of them have been carried over a still wider area in solution, and some ore masses are found in regions at a considerable distance from known occurrences

of igneous rock. Iron ores (hæmatite and limonite) are among the commonest of this type, often forming masses in limestones or other sedimentary rocks, such as those of Cumberland and the Forest of Dean. These deposits do not always represent the filling of cracks; in some cases they are replacements (p. 31).

Water Supply. Much water is obtained either by establishing reservoirs in upland areas or from wells: Manchester obtains its water from reservoirs in the Lake District, Birmingham and Liverpool from North Wales, while many villages and towns obtain much water by shallow or deep wells. Whatever their source, the geologist is closely concerned with the provision of these supplies.

If a well is put down in search of water, several factors must be borne in mind. Generally the supply of water is obtained from a pervious bed; a well sunk in clay, even to a depth of hundreds of feet, will not yield water. On the other hand, most sandstones and limestones will yield some water if other conditions are favourable. The movement of ground water has already been mentioned (p. 26). A well reaching a water-bearing bed below the water-table will normally supply water, although if the water-table falls during a drought the well may run dry. It may be remarked that a well is not usually sunk in the hope of reaching an underground "stream," as is often suggested; the well may be regarded as creating an artificial spring, water trickling from the pores or crevices of the water-bearing rock into the hole thus formed.

In the case of a dipping bed from which it is hoped to obtain water, the depth at which it is reached obviously depends on the amount of dip (*Fig.* 130a). Faults may also affect the question of supply, since a fault may seal-off a water-bearing bed completely; no supply would be expected at the well at X in *Fig.* 130b, although Y would yield water. Moreover the quantity of water obtained is definitely related to the amount sinking underground at the outcrop of the pervious bed, and thus the area which that occupies is of vital importance in determining the maximum yield of the well. If the outcrop is concealed by an impervious cover

(for example, of boulder clay, as in *Fig.* 130c) no supply can be hoped for.

In many cases it is necessary to pump the water from a well, but in others the water rises to the surface of its own accord; this occurs in *flowing* or *Artesian* wells. This flow is due to the pressure of the water contained in the pervious

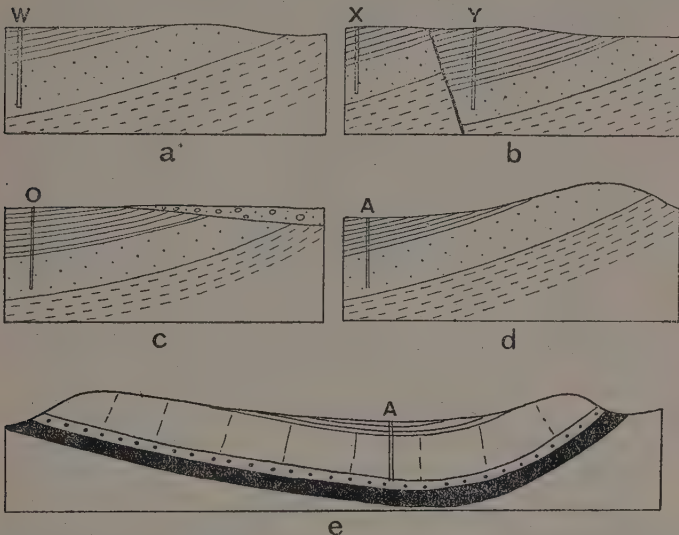


FIG. 130. Diagrams to show the location of wells. a, a well (W) sunk to a permeable stratum (dotted); b, a well (Y) in a similar position to that of a, and another well (X) whose yield is affected by the fault; c, a well (O) to a permeable stratum with boulder clay covering its outcrop and preventing the collection of water; d, a possible position for an Artesian well (A); e, a section across the London basin showing a well sunk through Lower Tertiary rocks into the Chalk.

bed, and it most commonly occurs when the top of the well is situated at a lower level than the water-table at the outcrop (*Fig.* 130d); it may most easily be explained by noting that the water is in continuity through the pores and crevices of the pervious bed, and the weight of the head of water

thus forces that in the well "to try to reach its own level." Much artesian water was formerly obtained in the London area by deep wells sunk through the Tertiary rocks down to the underlying Chalk (*Fig.* 130e); as the gathering grounds were situated in the hills on either side of the basin the water rose freely. Owing to the large number of wells sunk the water-table has fallen and pumping is now necessary in many cases.

In obtaining water supplies from wells (especially from shallow wells) the dangers of contamination must be considered. The positions of farms and cess-pits in relation to the gathering ground are important. Supplies obtained from limestones, in which the water often flows rapidly along enlarged joint planes, are much more liable to pollution than supplies from rocks in which the underground flow is slow.

Reservoirs for collecting water supplies in rainy upland regions are usually formed by damming a valley, the dam being placed, if possible, where the valley is narrow is order to hold up the maximum volume of water with a reasonably short dam. The bed rock under a reservoir should be impervious so that little water escapes by percolation.

The choice of the position of the dam requires very careful examination of the geological conditions. The base of the dam must be carried into solid rocks. The presence of a great thickness of boulder clay may thus add considerably to the cost of construction; a dam built on a foundation which is not strong enough or is not water-tight may collapse, and cause great loss. Similarly a dam should not be built across a fault, along which any further movement (during an earthquake for example) must damage the structure.

Oil. Oil is obtained from the rocks in two ways. Some is produced by the distillation of oil shales (p. 116), but the bulk occurs as natural crude oil which is obtained by means of wells. This oil is composed of various compounds of carbon and hydrogen which may yield on distillation several grades of petrol, lubricating oil and paraffin wax.

Oil occurs in porous rocks in much the same way as does water; it does not form pools or streams or reservoirs

(as is commonly suggested). Since oil is lighter than water, it is generally found above the water level. Water thus carries much oil upwards, and it escapes at the surface (possibly flowing out as pitch, as in Trinidad) if there is no oil-proof cover of impervious rock. Stores of petroleum are most frequently found where porous beds (such as sandstones), alternating with impervious layers, are folded into anticlines; the oil is held in the upper part of the folds by the water but cannot escape until tapped by a well (*Fig.* 131). It will be realised that when the oil is withdrawn it is not renewed (as is normally the case with water); oil wells run out after a number of years.

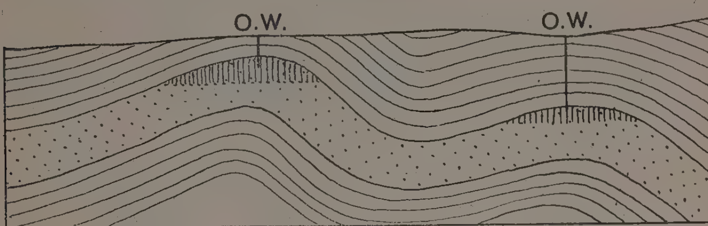


FIG. 131. Diagram to show a mode of accumulation of oil (vertical shading) in a permeable bed folded into anticlines; O.W., oil well.

Other problems concerning the occurrence and location of oil cannot be dealt with here; a large number of geologists are employed in elucidating the structures in many parts of the world and in selecting suitable sites for boring.

The origin of the oil presents a difficult problem, although it must certainly have been derived from organisms, either plants or animals. Their nature is not always clear, for they may not have lived contemporaneously with the deposition of the bed in which the oil is now found, since oil (like water) is capable of some movement in the rocks and may have migrated into that bed. Petroleum, it need hardly be said, is not normally found in igneous or metamorphic rocks (for the conditions which produced metamorphism would have decomposed the oil).

SUGGESTIONS FOR PRACTICAL WORK

Much field work can be carried out in many areas in connection with this part of the course. Visits to quarries in order to see how the working is related to dip and joints; the collection of details of building stones which have been used locally, with dates of the buildings and the state of weathering; data regarding village and other local water supplies.

Grinding of rock samples to form some idea of rate of wear, especially of road-stones.

Construction of simple model to show an Artesian basin; this may be made with sand and clay in a glass tank.

QUESTIONS

1. Give an account of the chief materials used in building in the area known to you. What do you consider to be their advantages and disadvantages?
2. Describe with the aid of diagrams the factors which would affect the location of a well to be sunk through impervious strata.
3. Explain the different forms assumed by the various kinds of iron ore deposit in England.

CHAPTER XVI

GEOLOGY IN THE FIELD

Field Work. At the beginning of this book the importance of outdoor work was stressed. Although reference is again made to field work here, the keen student will have recognised the value of making his own observations on many of the phenomena described in the intervening chapters. In the present chapter, however, a few lines of study which can be followed in many areas are indicated.

Interpretation of Dip Observations. In most parts of Britain it is possible to make dip readings. It is useful to supplement these by determining the thickness of given rock groups. For instance, if a series of sandstones dipping at 25 degrees is found to occupy a given breadth of country, their thickness can be measured graphically as shown in *Fig.* 132a (X Y). It must be remembered that the thickness is always measured at right angles to the bedding.

If the ground is not horizontal it is necessary to determine, at least approximately (from a contoured map if sufficient detail is available), the difference in height between the outcrop of the top of the beds and that of the base (*Fig.* 132b); this will not materially affect the result if the slopes are not very steep and the rock group is thick, but it may be important in other cases.

It is not necessary to have the whole of the sandstone group visible at the surface before determining its thickness. Provided that the readings of the dip are uniform at several points it may be assumed that the whole group behaves similarly. If, however, the bottom of the group is found to dip at an angle very different from that of the top, it is probable that the rocks are bent into a slight fold, and in drawing a section to measure the thickness a curve must be made

so that the top and bottom of the beds are parallel to one another (that is, so that the thickness remains constant even although the dip changes). This can best be done by drawing the dip angles at points on the section corresponding to their positions (at A and B on *Fig.* 132c) and drawing perpendiculars to the bedding at those points (A C, B D); the curve A D must now meet B D in a right angle. A similar con-

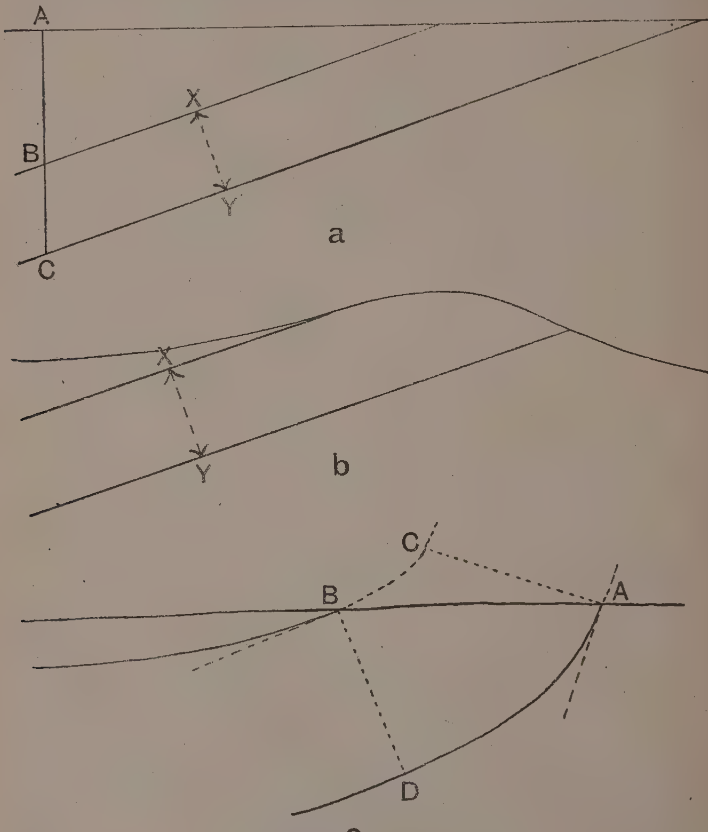


FIG. 132. Diagram to show the measurement of thickness of beds from surface observations. In a and b, the thickness is represented by XY.

struction will often be found useful in drawing sections across strata which are not dipping uniformly.

From dip observations also it is possible to determine the depth at which a given bed will be met in a well or a pit. This is illustrated by A B in *Fig.* 132a; in that case the well is dug in that bed for a distance B C, which is greater than X Y. It is interesting to compare the results so obtained with any which are available in local collieries or wells.

In this way the student will realise how a geologist is able to determine what rocks are present underground at any place, and at what depths they occur; he will understand more clearly how surface observations, possibly over an area of some square miles, can provide the data on which to base such estimates.

When walking in the country it is useful to look at the direction of dip for other reasons. It will be obvious that if we walk for any distance in the direction in which the rocks are dipping we are walking from older on to newer beds; if we walk against the dip, we go from newer on to older beds. In many areas walking with the dip will mean climbing steep scarp faces and walking down gentle dip slopes (compare *Fig.* 78a).

The Repetition of Outcrops. It may happen that on a long walk in a straight line, the same rock beds are seen several times. It is interesting to realise the various ways in which this may occur.

If sedimentary rocks are horizontal or nearly horizontal a walk over hills and valleys may take us across the same outcrop several times (*Fig.* 76). If the rocks are folded a similar repetition may be noticed even if the ground is level, but in such a case changes in the direction of dip will usually make the structure apparent (*Fig.* 80). The problem is not so easy if the rocks are overfolded, especially if the folding is of an *isoclinal* character, for it may then appear that a series of rocks of uniform dip is being crossed, until the inverted strata are recognised. In some cases a thin group showing isoclinal folding may at first be mistaken for a thick series of sediments showing similar characters and similar dips (*Fig.* 133).

The effects of strike faults in causing a repetition of outcrops have already been described (*Fig.* 89a).

The Observation of Faults. Occasionally a quarry or a natural exposure will show a fault in section, but as we have already mentioned, many of the largest faults are not known from sections but from other evidence. The nature of this evidence may vary greatly, but as a method of examining the evidence it is useful in many areas to take a copy of the local map of the Geological Survey (on the scale of either one inch or six inches to a mile) and to walk over the regions near the faults that are shown. The evidence on which the position of a fault was fixed may consist of discontinuous escarpments or of fault scarps; there

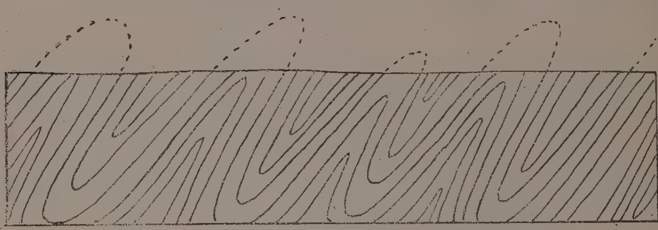


FIG. 133. Rocks showing isoclinal folding.

may be a hollow marking its line or a deeply eroded river valley; a line of springs may mark its course. The rocks on one side of a fault, followed in their direction of strike, will be replaced by other rocks on the opposite side, where the direction of strike may be different.

In following out these and other features the student cannot fail to acquire a grasp of structure which will help him in the interpretation of any other area.

Geological Mapping. It may be useful not merely to check the fault lines, but any other boundaries on the geological map, and to seek for reasons which led to the drawing of the boundaries. The student may wish to go further, and begin the making of a geological map of some area for himself. Even if the results are incomplete he cannot fail to gain from the effort a good deal of useful experience.

The first necessity is an accurate Ordnance Survey map, and it is best to use one on the scale of six inches to a mile. Even if no attempt is made to complete a geological map of the area, the recording in the correct places on the map of observations of dip will in itself be a very useful exercise. If all the quarries and natural exposures, in cliffs or stream beds, are visited and the observations made there are recorded on the map (first with a hard sharp pencil, and then with a fine pen and " Indian " ink) a good beginning will have been made.

But it may be that there are few exposures in the particular area, and that the gaps in his information are so considerable that the student begins to wonder how a geologist could make a complete map of the whole area without digging holes to see what lies beneath. Let it be understood that this practice is scarcely ever adopted; the skilled field worker can discover evidence even where there are scarcely any exposures. The stones around rabbit holes often afford invaluable clues to the rocks beneath, while the colour and nature of the soil in many areas give useful information. Linked with this is the character of the vegetation, for there are many plants which are peculiar to limestone regions, as there are others which show a marked preference for sandy or other soils. A belt of marshy ground marking the seepage at the base of a pervious bed may be easily traceable and may make it possible to map a boundary.

Still more important are the changes in the slopes of the land. Even where there are no conspicuous hills or ridges, nearly every change of slope has some meaning in the interpretation of the geological structure. To trace a hard bed which makes a slight rise in a field from one place where it is seen, perhaps in the bed of a stream, to the next exposure a mile or more away, is an experience which convinces the worker of the importance of slight irregularities in the form of land.

Possibly the easiest place to begin geological mapping in many areas is along the border of an alluvial tract, and for a young geologist to map the boundary of the alluvium is a very useful beginning. Later he may find river terraces which may not be much more difficult to follow.

The suggestions given above are for work mainly of a structural nature. Most areas will afford some such problems. There are, however, numerous other observations which can be made. In many areas the search for fossils can be carried on steadily, and as soon as the more abundant forms have become familiar, attention can be paid to the less usual types. It must always be borne in mind by a geological student that a vast number of new forms still await discovery, and that in many parts of the country (as much where fossils are rare as where they are common) new finds are to be expected. The finding of poorly preserved and fragmentary fossils in places where they have never been known may be more important than the collecting of perfect specimens where reasonably good ones have been obtained before.

In taking its students out-of-doors, giving them an eye for country and offering them always a chance of finding something of real interest and value, geology has a unique place among the sciences.

QUESTIONS

1. A series of sandstones dipping east at 30 degrees outcrops in horizontal ground; the base is seen at the surface 100 yards west of the top. Find the thickness of the bed. At what depth would you expect it to occur at a point 500 yards to the east? If it were found there at a smaller depth what possible explanations could you offer?
2. Write a concise account of the geology of an area you have studied in the field. Mention any quarries or other exposures you have visited, and describe briefly the specimens you collected. (C.W.B., 1933.)
3. Describe both topographically and geologically the characters of any river valley with which you are familiar. (C.W.B.Hr., 1935.)
4. Explain briefly what a geological map is meant to show. (C.W.B., 1936.)
5. The base of a limestone is seen at a point 250 feet above sea level dipping due east at 40 degrees; the top of the limestone is seen with the same dip 500 yards east of the first point at 350 feet above sea level. Find graphically or otherwise the thickness of the limestone. If a pit were sunk vertically at the second point for what distance would the shaft be in limestone?

SUGGESTIONS OF BOOKS FOR REFERENCE

The books mentioned below are comparatively inexpensive and are suitable for pupils to refer to.

Several of the general text-books on geology should be available for reference. Lake and Rastall's *Text Book of Geology* and Watts' *Geology for Beginners* may be mentioned in this connection. Many older text-books, even when unsuitable in their approach to the subject, contain useful illustrations.

In mineralogy, Prof. Read's revision of *Rutley's Mineralogy* forms the best general introduction. L. J. Spencer's *The World's Minerals* is also suitable.

Of books on fossils there is not such a wide choice and no one book quite meets the needs of school pupils: Prof. A. M. Davies' *Introduction to Palæontology* or Prof. H. L. Hawkins' *Invertebrate Palæontology* are the most suitable. The guides issued by the British Museum (Natural History) may also be recommended for pupils' reading.

The present book gives only a slight treatment of scenery and of the structure of England and Wales, and for fuller details of many aspects, with illustrative diagrams, the reader is advised to consult the author's *Scenery of England and Wales*. The study of local geology may suitably be begun in many parts of Britain by the use of the newly published handbooks on British Regional Geology; other Geological Survey memoirs are essential for reference in those areas where they are available. Many of the regional pamphlets issued by the Geologists' Association of London are also invaluable as a basis of local study.

For further suggestions regarding the applications of geology, Prof. Shand's *Useful Aspects of Geology* should be consulted.

In addition, a selection of more popular books on geology should be available for general reading. Prof. Shand's *Earth Lore* and Gregory's *Geology of To-Day* may be mentioned; some of the older books by Geikie and Grenville Cole are also particularly attractive.

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